GEOPHYSICAL SURVEYS FOR
GROUND WATER EVALUATION
NEAR THE KAWAIHAE EXPLORATORY WELL
NORTHEAST OF KAWAIHAE
ISLAND OF HAWAII

Prepared For:

State of Hawaii
Department of Land & Natural Resources
Division of Water Resource Management
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(Our Project #90041)

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1.0 INTRODUCTION

Time domain electromagnetic (TDEM) geophysical surveys were conducted to assist in ground water resource evaluation near the recently drilled Kawaihae exploratory well northeast of the town of Kawaihae, Island of Hawaii. The surveys were performed by Blackhawk Geosciences, Inc. (BGI) between September 9 and September 15, 1990 for the State of Hawaii (State).

The location of the measurement stations and the interpretations and conclusions derived from this survey were influenced by a prior TDEM survey conducted north of Honokoa Gulch for Kohala Joint Venture (KJV). By agreement from all concerned parties the results of the survey north of Honokoa Gulch are used in this report.

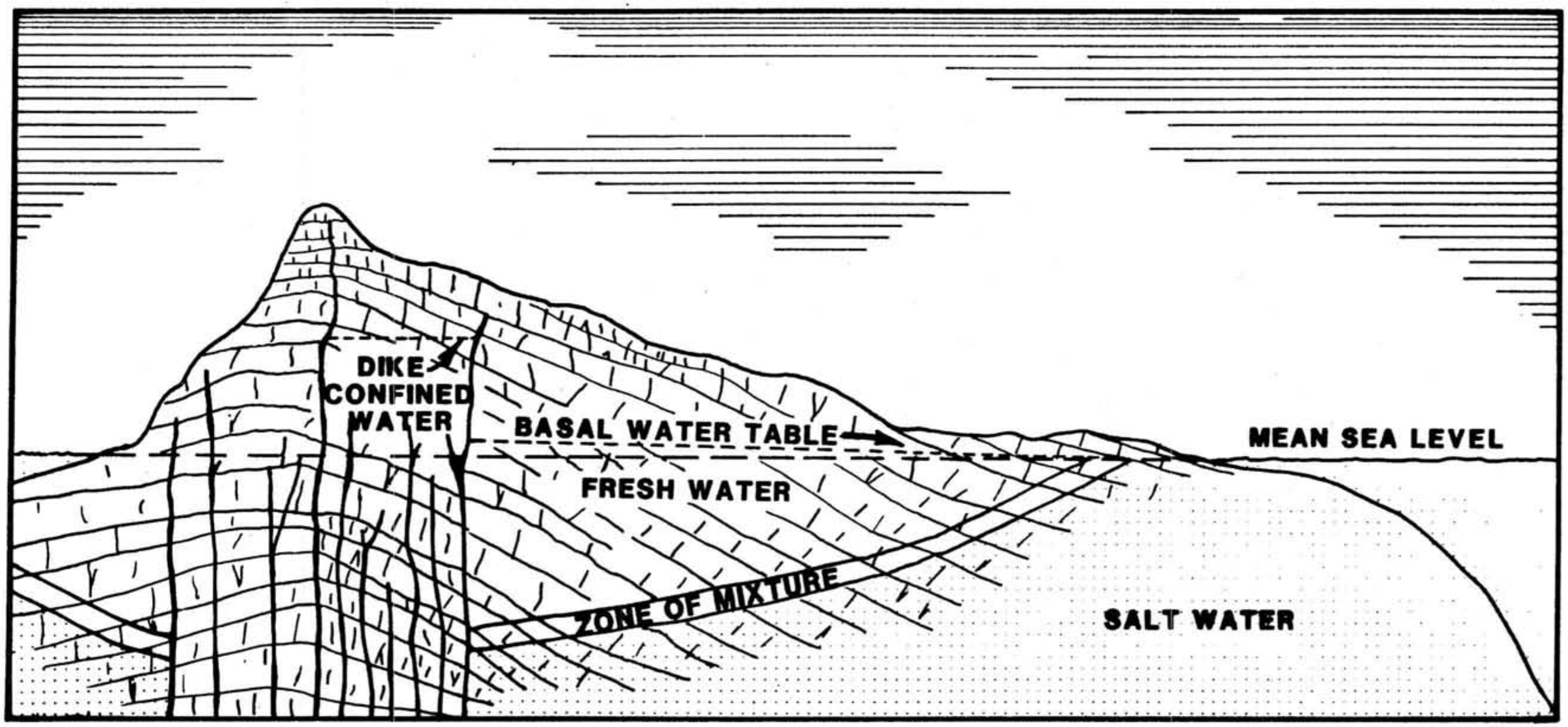
The primary objective of the geophysical survey was to assist in characterizing the hydrologic regime in the vicinity of the Kawaihae well. Drilling results disclosed a low static water level (1.1 ft above msl) in the well. Important reasons for conducting a geophysical survey were (i) to evaluate if such low static water levels are characteristic of a large area, and (ii) if perhaps the potential for better water resources exist elsewhere nearby. The basis for geophysical surveys for ground water evaluations on volcanic islands are illustrated in Figure 1-1. The volcanic rocks are generally highly permeable and this allows rainwater to percolate with little impedance directly downward through the island mass. The fresh water in these island settings is generally found in two environments:

1. Basal fresh water. The high permeability of the volcanic rocks allows sea water to enter freely under the island, and a balance is reached where a lens of fresh water floats on sea water. In cases of hydrostatic equilibrium, the Ghyben-Herzberg principle states that for every foot of fresh water head above sea level there will be 40 ft of fresh water below sea level.

2. Dike-confined waters. Typically, above the rift zone intrusive dikes originating from a magma source below can form ground water dams, and behind these natural dams significant quantities of ground water can be stored.

Because the electrical resistivity of rock formations is highly dependent upon the salinity of ground water, electrical surface geophysical techniques can map the depth to salt water, and the thickness of the fresh water lens can then be estimated using the Ghyben-Herzberg principle. The impetus for using geophysics is that the cost of a geophysical sounding is about one-thousandth the cost of completing a well at elevations above

1,000 ft. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and well completion depths. The specific geophysical method employed was time domain electromagnetic (TDEM) soundings. This method was selected because it has proven effective in prior surveys in similar settings in Hawaii.



BLACKHAWK GEOSCIENCES, INC.

SCHEMATIC HYDRO-GEOLOGIC CROSS SECTION

State of Hawaii Division of Water Resources Management

PROJECT NO: 90042

FIGURE 1-1

2.0 LOGISTICS AND DATA ACQUISITION

2.1 GENERAL

The TDEM survey was accomplished by a three man crew consisting of two BGI personnel and one local temporary field helper. The location of the TDEM soundings were determined from consultation with State personnel and were partially based on the results from a prior geophysical survey conducted north of Honokoa Gulch for Kohala Joint Venture (KJV). TDEM measurements were initially made near the Kawaihae Exploratory Well at about the 1,300 ft and 1,600 ft elevation, south of Honokoa Gulch. Several other soundings were also acquired north of Honokoa Gulch on Hawaiian Homelands Property. The TDEM sounding locations for this survey and the March and April 1990 surveys for KJV are shown on Figure 2-1. The report of the KJV survey are contained in Appendix C, and the results are also incorporated in this report.

During the three days of field work a total of 5 soundings were acquired around the well site. A daily log of field activities is given in Table 2-1. Soundings locations were surveyed using a compass and hip chain from known landmarks (i.e., road junctions, rock walls) located on the field map. Elevations of sounding centers were measured with an altimeter in the field and checked with USGS field maps. Transmitter loop sizes of 1,000 ft by 1,000 ft were used on all of the TDEM soundings to detect the salt water interface.

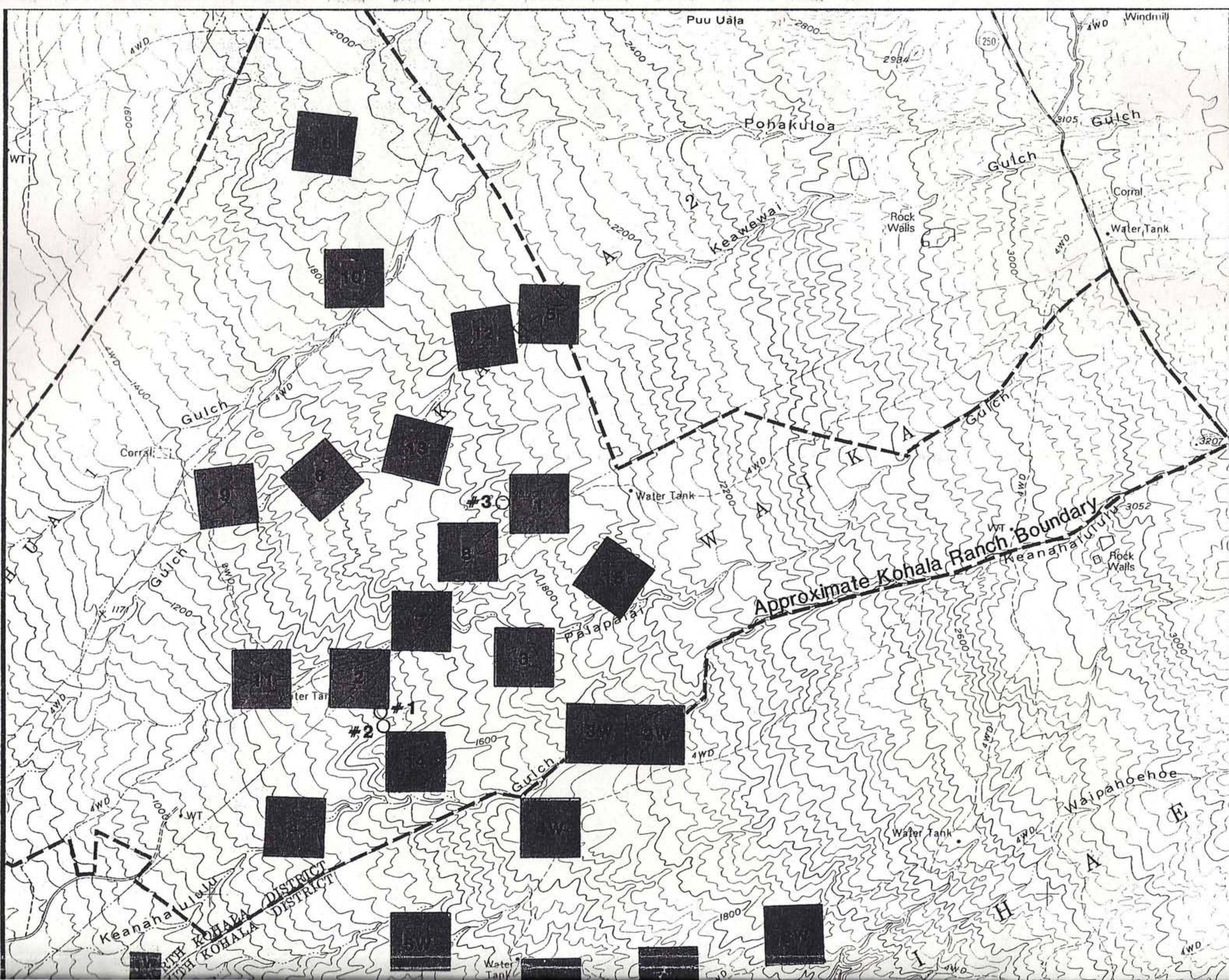
Table 2-1. Daily log of field activities

Date (1990)	Activity
September 6	Mobilization from Denver, CO to Kailua-Kona, HI in conjunction with other geophysical surveys.
September 9	Reconnaissance of Kawaihae Exploratory Well Project Area for sounding sites. Data acquired on soundings 1 and 2.
September 10	Data acquired on sounding 3.
September 15	Reconnaissance for sounding sites on north side of Honokoa Gulch. Data on soundings 4 and 5.
September 19	Demobilize equipment and BGI personnel.

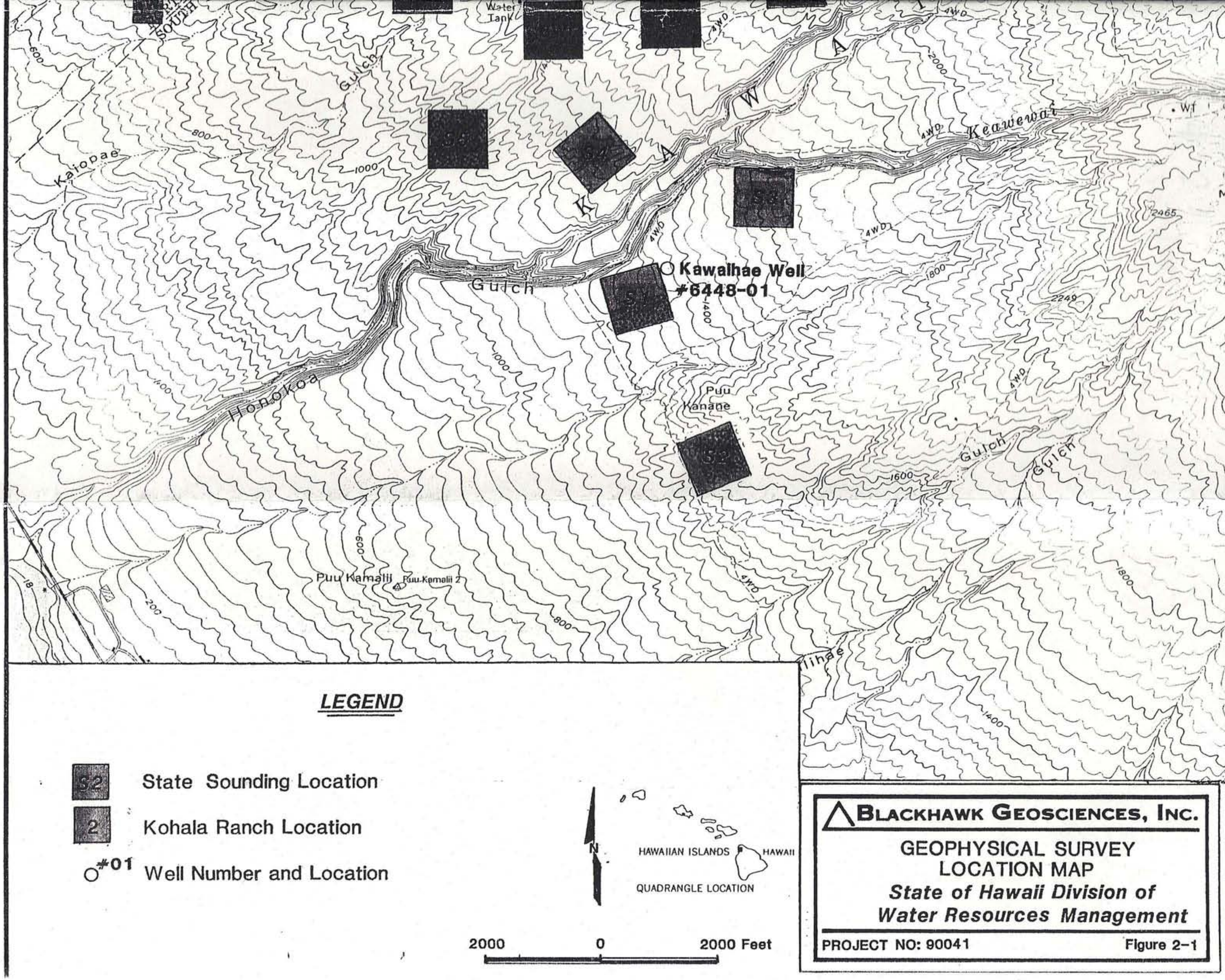
(September 7, 8, 11 through 14, and September 16 through 18 are days of field work at other Hawaii locations)

2.2 PROCEDURES

The Geonics EM-37 TDEM system was utilized on this survey. The system basically consists of a transmitter and a receiver. The transmitter loop is constructed of 10 to 12 gauge insulated copper wire. The wire is laid on the ground surface in a square loop varying in size, depending upon the required depth of investigation (larger loop sizes for deeper measurement). A transmitter and motor generator are connected into the non-grounded loop at one corner. A time-varying current is pulsed through the wire at two different base frequencies. The TDEM receiver measures and records the decay of the vertical magnetic field through a receiver coil placed at the center of the non-grounded transmitter loop. Receiver coils with effective areas of 100 m^2 and 1,000 m^2 were utilized at base frequencies of 3 Hz and 30 Hz. During data acquisition numerous transient decays are collected with the receiver for each sounding. Readings were acquired at several receiver gains with opposite receiver polarities for each sounding location. The readings were stored in a DAS-54 solid state data logger, and were nightly transferred to a personal computer for processing. A technical note is given in Appendix A which describes and illustrates the principles of TDEM.



Puu Uala
Windmill
Pohakuloa
Gulch
Corral
Rock Walls
Water Tank
Keawewai
Corral
#3
Water Tank
Approximate Kohala Ranch Boundary
Keanahalululu
Rock Walls
Palapalai
#1
#2
Waipahoehoe
Water Tank
Keanahalululu
DISTRICT
DISTRICT



Water Tank
Gulch
Kaiopae
Keawewai
4WD
Kawaihae Well
#6448-01
Gulch
Honokoa
Puu Kanane
Gulch
Gulch
Puu Kamalii
Puu Kamalii 2
2465
2249
2000
1800
1600
1400
1000
800
600
200
LEGEND
S2
State Sounding Location
2
Kohala Ranch Location
#01
Well Number and Location
N
HAWAIIAN ISLANDS
HAWAII
QUADRANGLE LOCATION
2000
0
2000 Feet
BLACKHAWK GEOSCIENCES, INC.
GEOPHYSICAL SURVEY
LOCATION MAP
State of Hawaii Division of
Water Resources Management
PROJECT NO: 90041
Figure 2-1

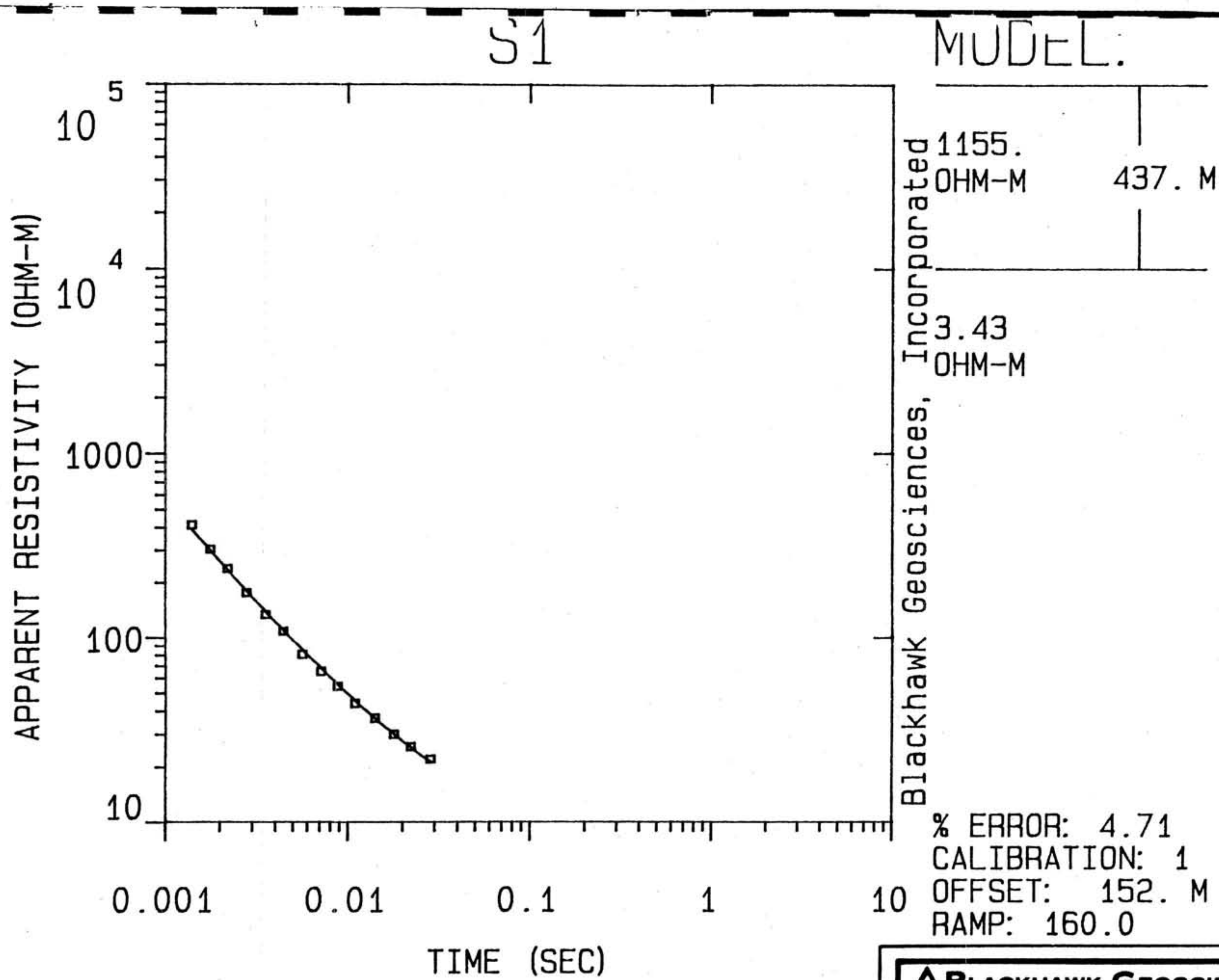
3.0 DATA PROCESSING

The field data acquired each day was transferred from the DAS-54 data logger to a personal computer. The data for each sounding location is edited and combined (both 3 Hz and 30 Hz frequencies) to produce a transient decay curve. This decay curve is transformed into an apparent resistivity curve, which is entered into an Automatic Ridge Regression Transient Inversion Program (ARRTI). From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers, and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to float freely.

An example data set is given in Figures 3-1 and 3-2 for sounding S1. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed behavior of the true resistivity layering shown on the right. Figure 3-2 is the inversion table and it lists in column 4 the error between measured and computed data in each time gate.

The apparent resistivity curves and data sheets for all of the State soundings are contained in Appendix B.



BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET

State of Hawaii Division of Water Resources Management

PROJECT NO: 90041 **Figure 3-1**

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		390.1	1280.0		
1155.34	437.4	-47.3	-155.0	0.4	0.4
3.43					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.40E-03	4.13E+02	3.89E+02	6.222	
2	1.77E-03	3.04E+02	2.97E+02	2.472	
3	2.20E-03	2.38E+02	2.32E+02	2.409	
4	2.80E-03	1.76E+02	1.78E+02	-1.003	
5	3.55E-03	1.34E+02	1.38E+02	-2.964	
6	4.43E-03	1.09E+02	1.09E+02	-0.463	
7	5.64E-03	8.09E+01	8.53E+01	-5.152	
8	7.13E-03	6.54E+01	6.77E+01	-3.387	
9	8.81E-03	5.44E+01	5.54E+01	-1.842	
10	1.10E-02	4.42E+01	4.55E+01	-2.809	
11	1.41E-02	3.68E+01	3.65E+01	0.744	
12	1.80E-02	3.01E+01	3.00E+01	0.365	
13	2.22E-02	2.58E+01	2.54E+01	1.838	
14	2.85E-02	2.21E+01	2.12E+01	4.360	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
CLHZ ARRAY, 14 DATA POINTS, RAMP: 160.0 MICROSEC, DATA: S1
0909 002N 001S Z OPR XTL H 4 8+100
Ch.21 = 0.16 Ch.22 = 0.089 Ch.23 = 15 Ch.24 = 9
RMS LOG ERROR: 2.00E-02, ANTILOG YIELDS 4.7135 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.01		
P 2	-0.04	0.93	
T 1	0.01	0.00	1.00
	P 1	P 2	T 1

BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET

State of Hawaii Division of Water Resources Management

PROJECT NO: 90041 Figure 3-2

4.0 RESULTS AND INTERPRETATION

4.1 CORRELATING GEOELECTRIC SECTIONS WITH HYDROGEOLOGIC INFORMATION

Thus, the results of the interpretations of individual soundings is the resistivity layering (geoelectric section) of the subsurface. The translation of resistivity layering into meaningful hydrogeologic information is generally accomplished in two ways:

(1) Calibrating the geophysical interpretation at a well. The Kawaihae Exploratory Well (#6448-01) was available for comparison, as well as three other wells on the Kohala Ranch property (wells #1, 2 and 3, Fig. 2-1).

The Kawaihae Exploratory Well had a static water level of 1.1 ft above msl. Assuming validity of the Ghyben-Herzberg relation the interface between fresh/brackish water and salt water is expected at about 45 ft below msl. The soundings in the vicinity of the well (soundings S1 through S5 - see Appendix B) show a two-layer resistivity structure - an upper layer with a resistivity greater than 500 ohm-m, and a lower layer with a resistivity less than 3 ohm-m. Comparison of well information with TDEM derived geoelectric sections, therefore, suggest:

(a) resistivities greater than 500 ohm-m are characteristic of (i) unsaturated volcanics above the water table, and (ii) volcanics saturated with fresh/brackish water below the water table and above the interface with salt water; and

(b) resistivities less than 3 ohm-m are characteristic of volcanic rock saturated with salt water.

(2) Using available knowledge about the relation between resistivity values and hydrogeology. In many prior surveys over the volcanic rocks of Hawaii, rocks saturated with salt water also showed resistivities less than 5 ohm-m, and dry and fresh-brackish water saturated volcanic rocks and intrusives displayed very high resistivities (greater than 1,000 ohm-m).

Thus, where a very conductive layer (< 5 ohm-m) is detected below sea level, this layer is expected to represent salt water saturated volcanics. Static water levels (heads) can subsequently be calculated from the geoelectric sections by using the Ghyben-Herzberg principle. This principle states that, under conditions of static equilibrium, for every foot of fresh water above sea level there will be about forty feet of fresh water below sea level. An illustration of the Ghyben-Herzberg principle is given in Figure 4-1. This principle, however, assumes static equilibrium and may not apply in close proximity to ground water damming structures (i.e., dikes, rifts, areas of high hydraulic gradients).

4.2 INTERPRETATION MAP

The results of the 5 State soundings and the 24 Kohala Ranch soundings are summarized on Figure 4-2. The following information is summarized on this figure:

(1) The soundings are classified in two categories:

(i) soundings in which no layer of low resistivity (< 5 ohm-m) was detected within the effective exploration depth of the measurement. In this area ground water is expected to be trapped by ground water damming structures. The interpreted boundary of this area is shown on the map in Figure 4-2. Wells #1, 2 and 3 are located in this area. The head observed at well #3 was 150 ft above msl and is typical of structural controlled ground water; and

(ii) soundings in which a layer of low resistivity (< 5 ohm-m) was detected. This layer is interpreted to represent the interface between fresh/brackish and salt water. Ground water in this area is expected to occur in a basal mode with a lens of fresh water floating on salt water.

(2) For soundings which detected the interface between fresh/brackish water and salt water the elevation in ft of the interface is listed.

(3) The elevation of the salt water interface is contoured.

Several features stand out on the interpretation map:

(1) The contours are approximately perpendicular to the interpreted boundary between basal and structurally controlled water. It suggests a dominant ground water flow direction in a westerly direction near parallel to the boundary of the mapped structure.

(2) The area where ground water is expected to be controlled by structures is wedged shaped and extends from about 1,000 ft elevation near sounding 4 (on the Kohala Ranch property) and widens with increasing elevation toward the northeast.

(3) The gradients of the contours are highest in an area just north of the Honokoa Gulch. The results of the TDEM survey suggest a complex ground water regime near the Honokoa Gulch. This can be further illustrated by constructing a hydrogeologic cross-section perpendicular to the coast consistent with the TDEM derived data. Such a cross section is shown on Figure 4-3. Since no local recharge or discharge is known to occur along the cross section, the flow rate along the cross section must be expected to be basically the same. If this is true a large hydraulic transmissivity contrast must occur where the gradient is steep. A nominal hydraulic gradient and high permeabilities are expected from about the Kawaihae Exploratory Well to the ocean, and high hydraulic gradients with low transmissivities east of the well.

Such large contrasts in transmissivity would be unusual. Possible causes for such a contrast could be:

(1) A trachyte flow several hundred feet thick. Trachytes are volcanic flows of fine grained intrusives and they can be of low permeability.

(2) A series of north-south oriented leaky ground water damming structures. The origin of these structures could be from the same source as the inferred ground water damming structures on the Kohala Ranch.

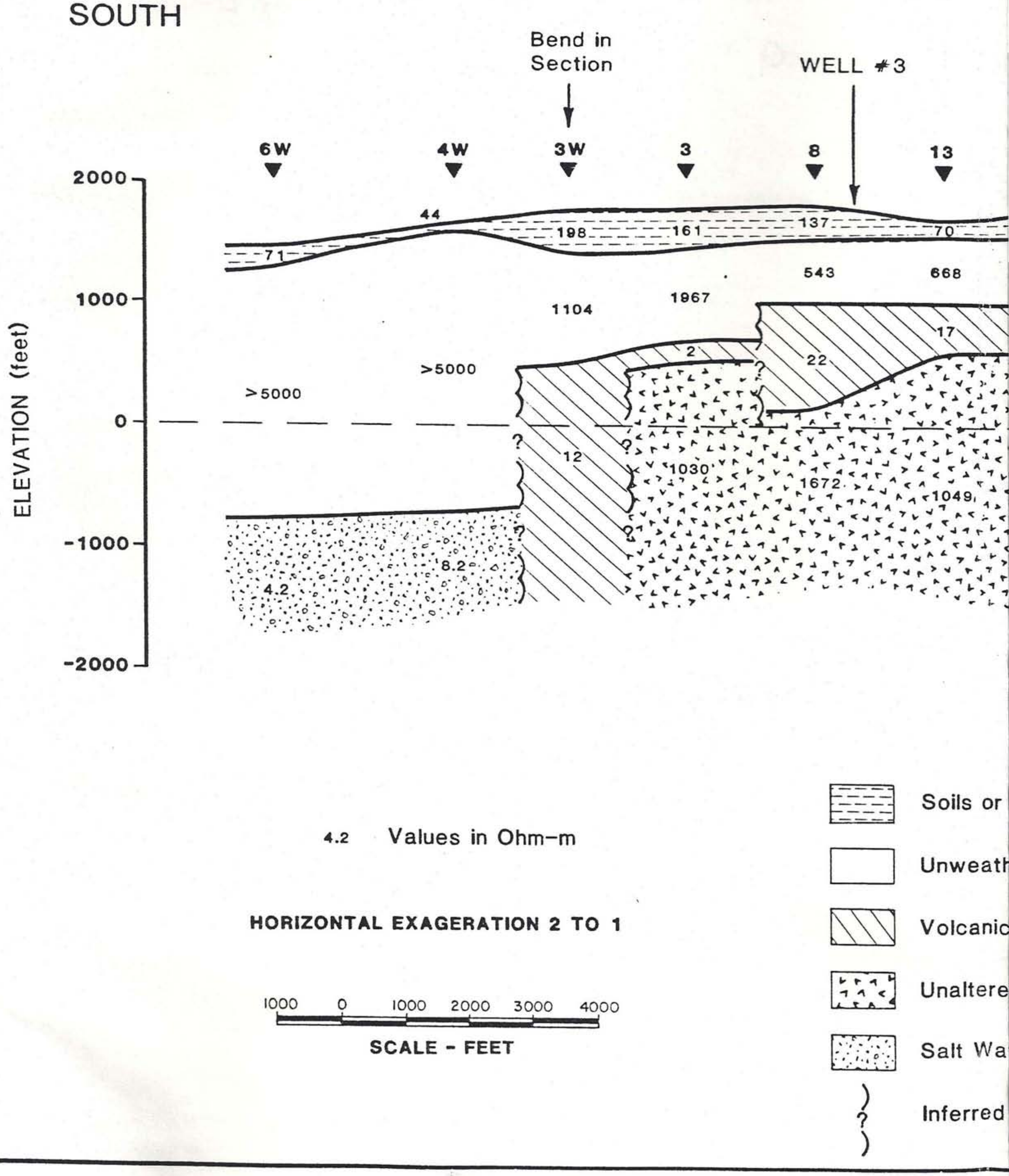
If indeed lower permeabilities are the cause of the change in gradient, than the higher heads observed north of the Kawaihae Exploratory Well may not directly convert to a successful well. Lower permeabilities of the rock could result in low yield.

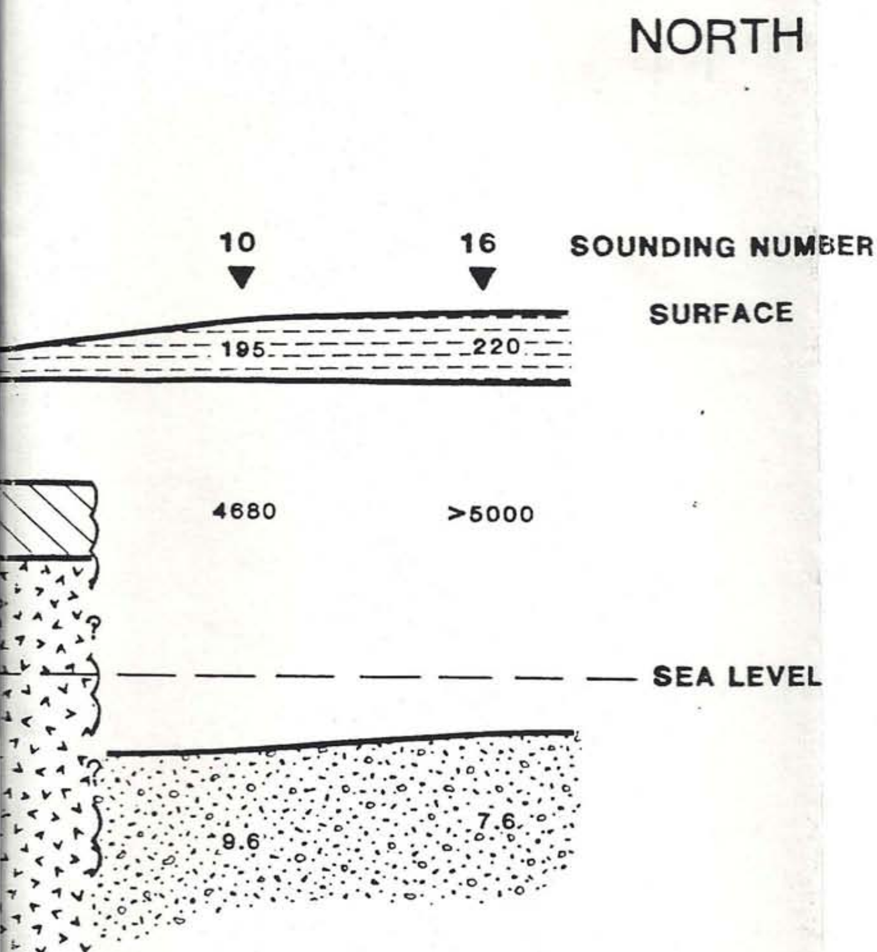
Table 4-1 lists the approximate thicknesses of the fresh-brackish water lens computed from the elevations of the salt water interface derived from TDEM soundings. The list includes the five State soundings and the six soundings taken south of the interpreted boundary between basal and structure controlled water on the Hawaiian Homelands Property for the KJV.

Table 4-1. **Hydrogeologic information derived from TDEM soundings**

Sounding #	Surface Elevation (ft)	Approximate Thickness of Fresh/Brackish Water Lens (ft)
S1	1280	155
S2	1350	239
S3	1600	291
S4	1320	236
S5	1200	75
1W	830	98
4W	1665	771
5W	1340	484
6W	1450	778
7W	1680	905
8W	1885	1000?

When the surface elevations are plotted versus the approximate thicknesses of fresh water lenses (Fig. 4-4), it provides further evidence of the existence of two regions with different hydrogeologic characteristics. The head observed in the Kawaihae Exploratory Well is consistent with the results from TDEM soundings S1 through S5.


SOUTH
Bend in Section
WELL #3
6W
4W
3W
3
8
13
2000
1000
0
-1000
-2000
ELEVATION (feet)
44
71
198
161
137
70
543
668
1104
1967
17
2
22
>5000
>5000
12
1030
1672
1049
8.2
4.2
4.2 Values in Ohm-m
HORIZONTAL EXAGERATION 2 TO 1
1000 0 1000 2000 3000 4000
SCALE - FEET
Soils or
Unweath
Volcanic
Unaltere
Salt Wa
Inferred



LEGEND

or Weathered Volcanics

athered Volcanics

nic Ash Flows or Altered Volcanics

ered Volcanics or Intrusives

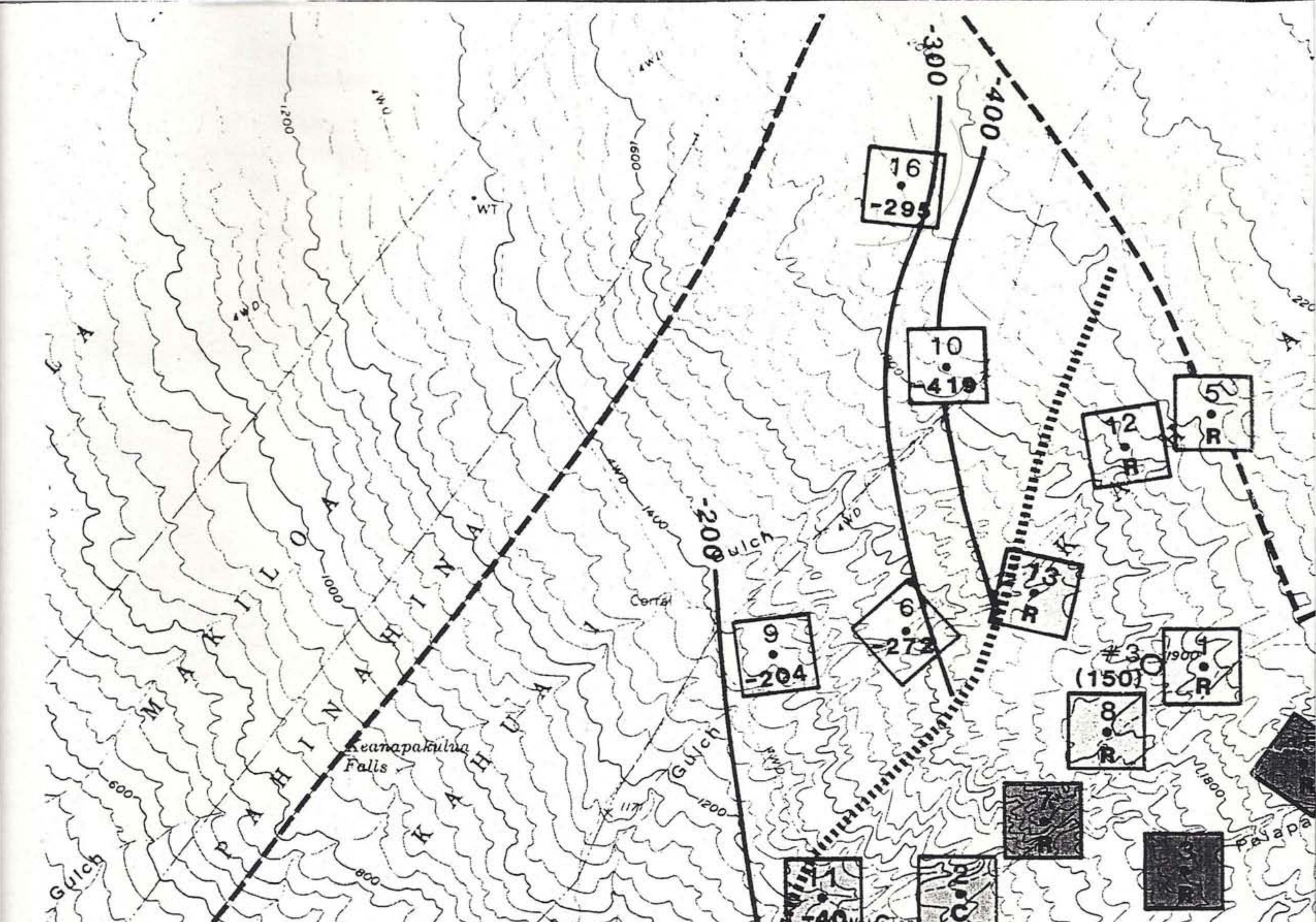
Vater Saturated Volcanics

ed Geologic Structure

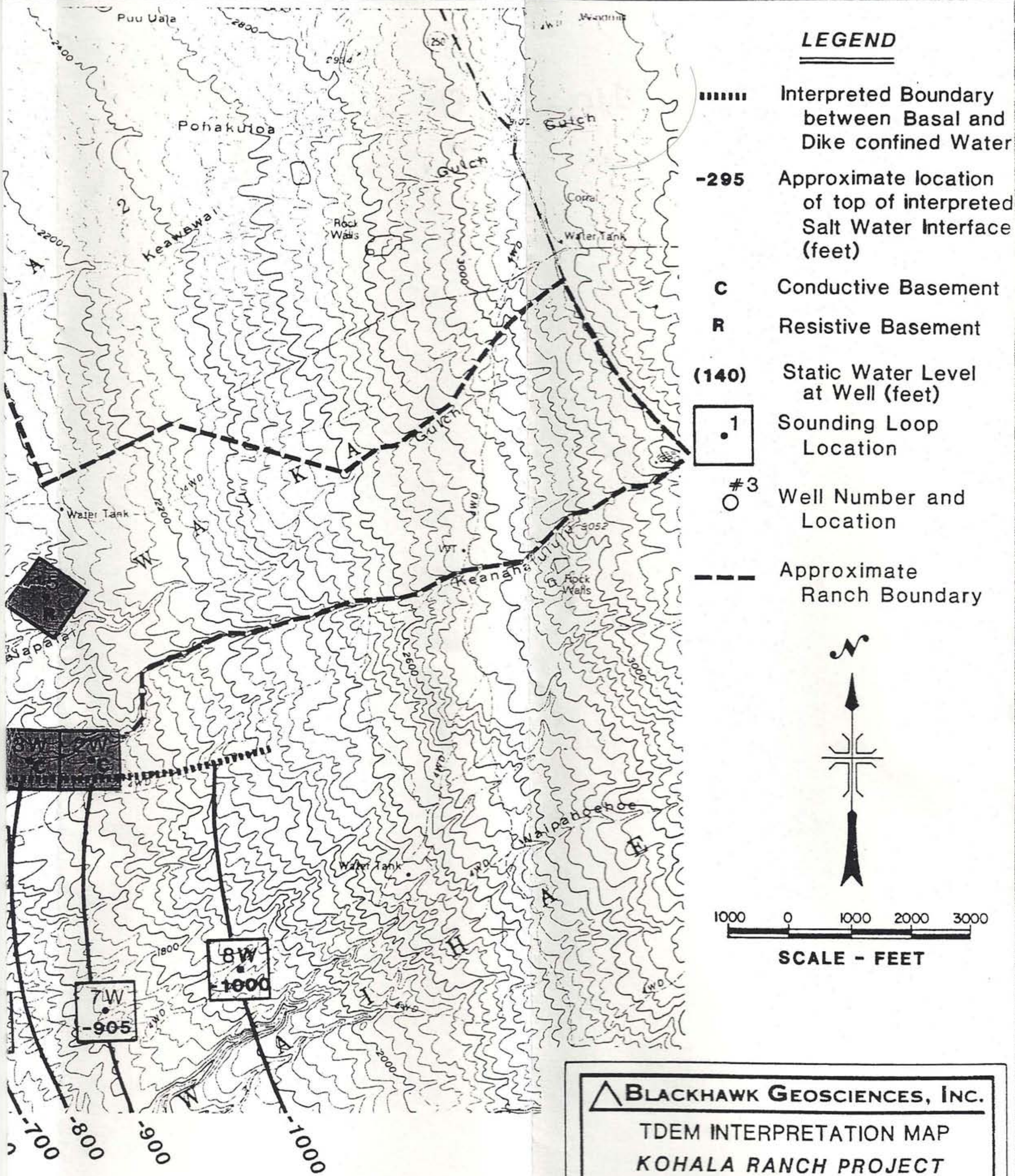
BLACKHAWK GEOSCIENCES, INC.

TDEM SURVEY
GEOLOGIC CROSS SECTION
KOHALA RANCH PROJECT
NORTH KOHALA, HAWAII

PROJECT NO.: 90016 FIGURE 4-1



MAKILOA
PAHINAHINA
KAHUA
Keanapakulua
Falls
Waiokanalopaka
Falls
Gulch
Corral
Palapa
16
-295
10
-419
5
R
12
R
13
R
6
-272
9
-204
#3
(150)
8
R
7
R
3
R
1
-40
C
2
C
#1
#2
(6)
14
C
4
C
3W
4W
-771
5W
-484
1W
-92
6W
-778
-100
-200
-300
-400
-500
-600
-700



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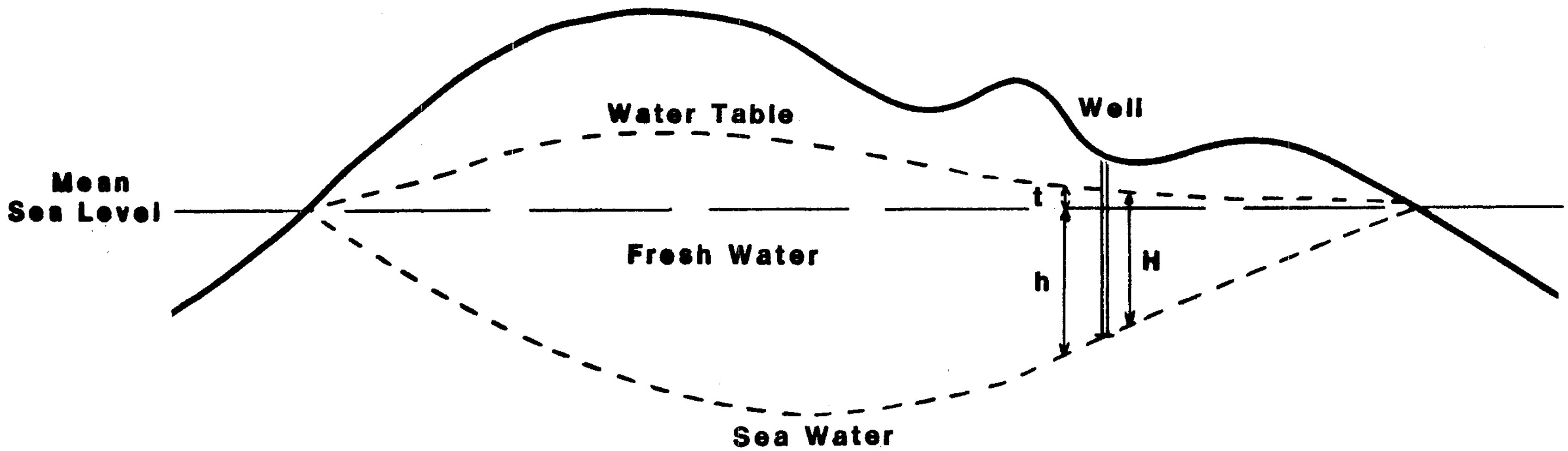
TDEM INTERPRETATION MAP

KOHALA RANCH PROJECT
NORTH KOHALA, HAWAII

PROJECT NO.: 90016 FIGURE 4-2



$t = 1/40\ (h)$

FROM: HERZBERG

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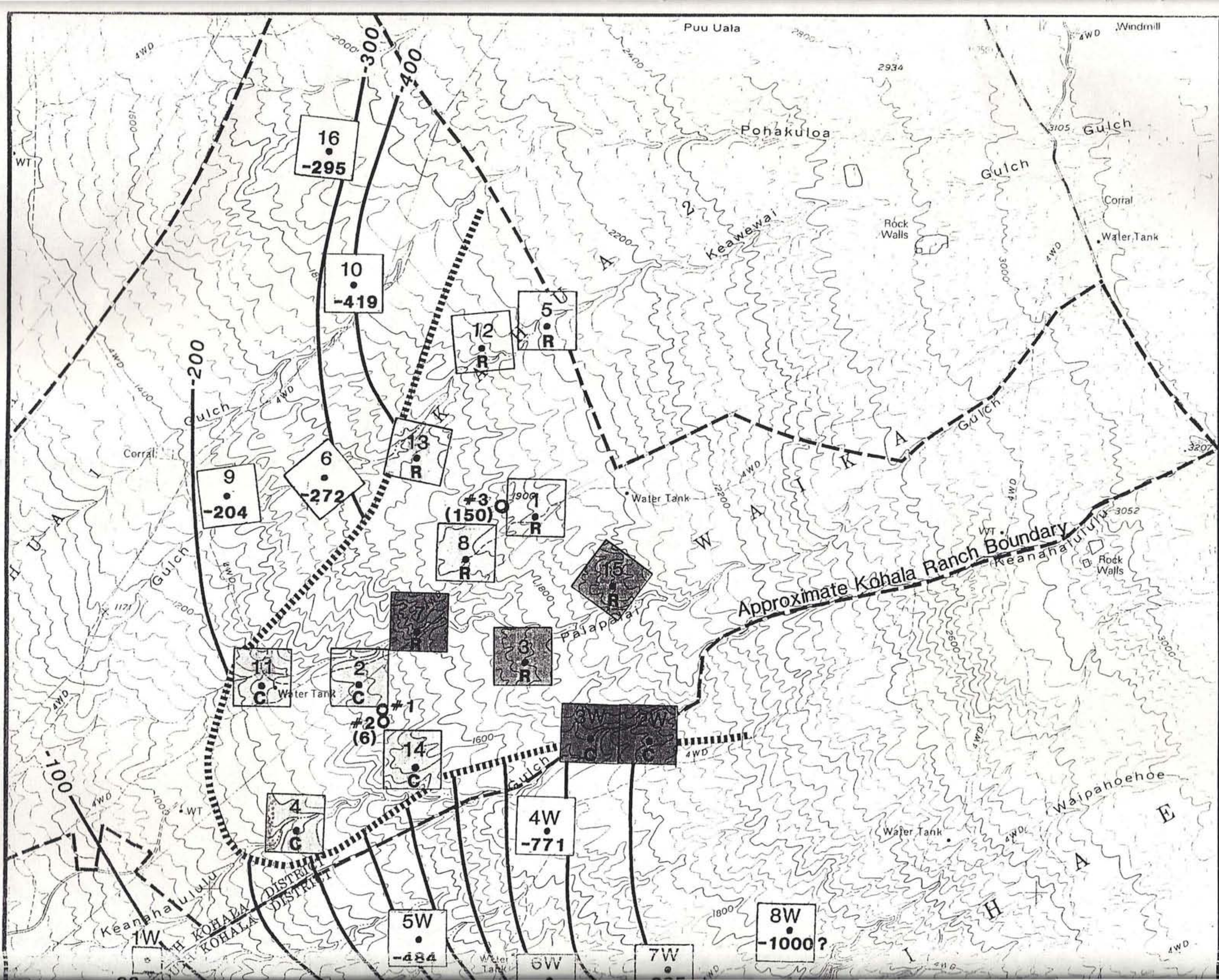
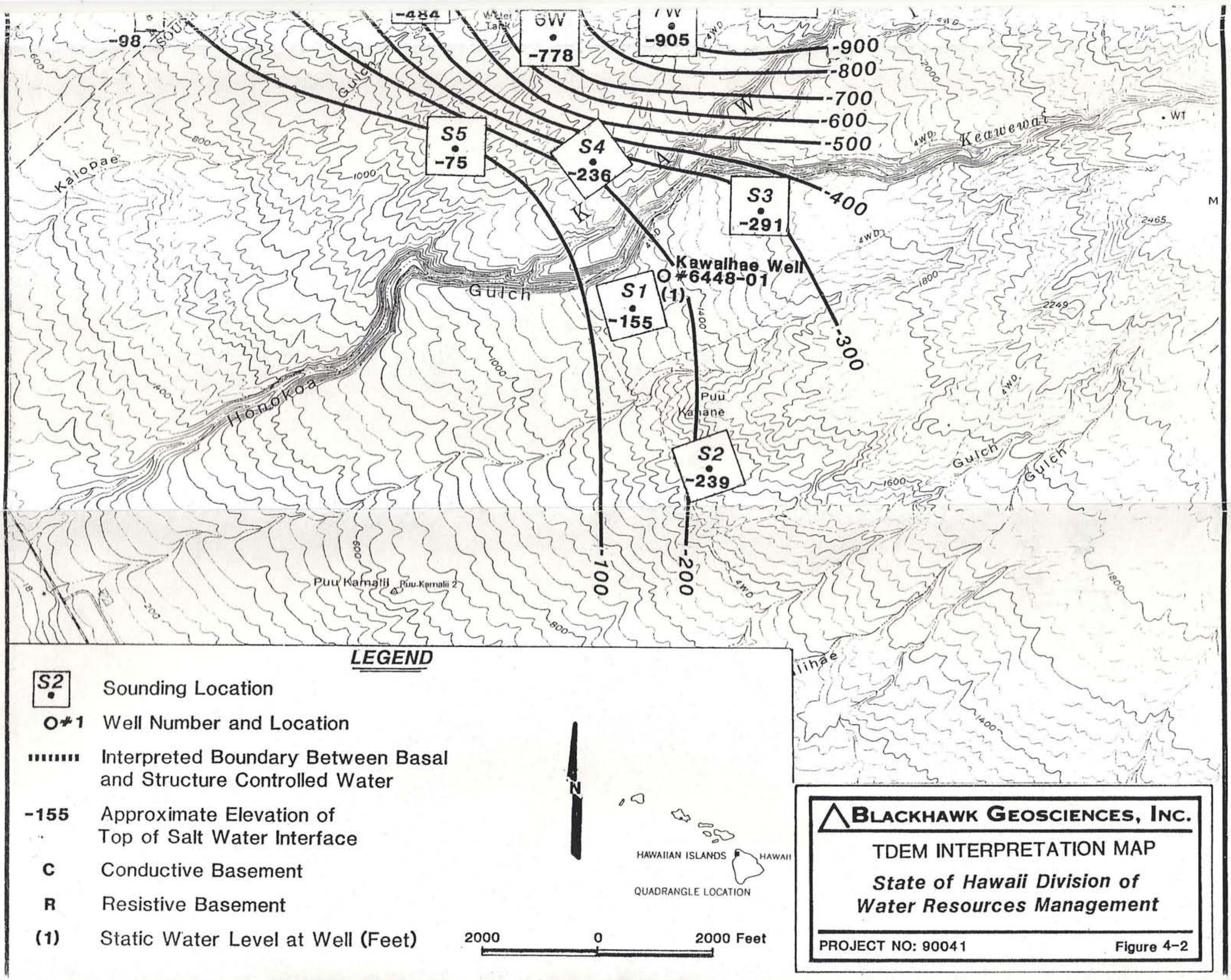
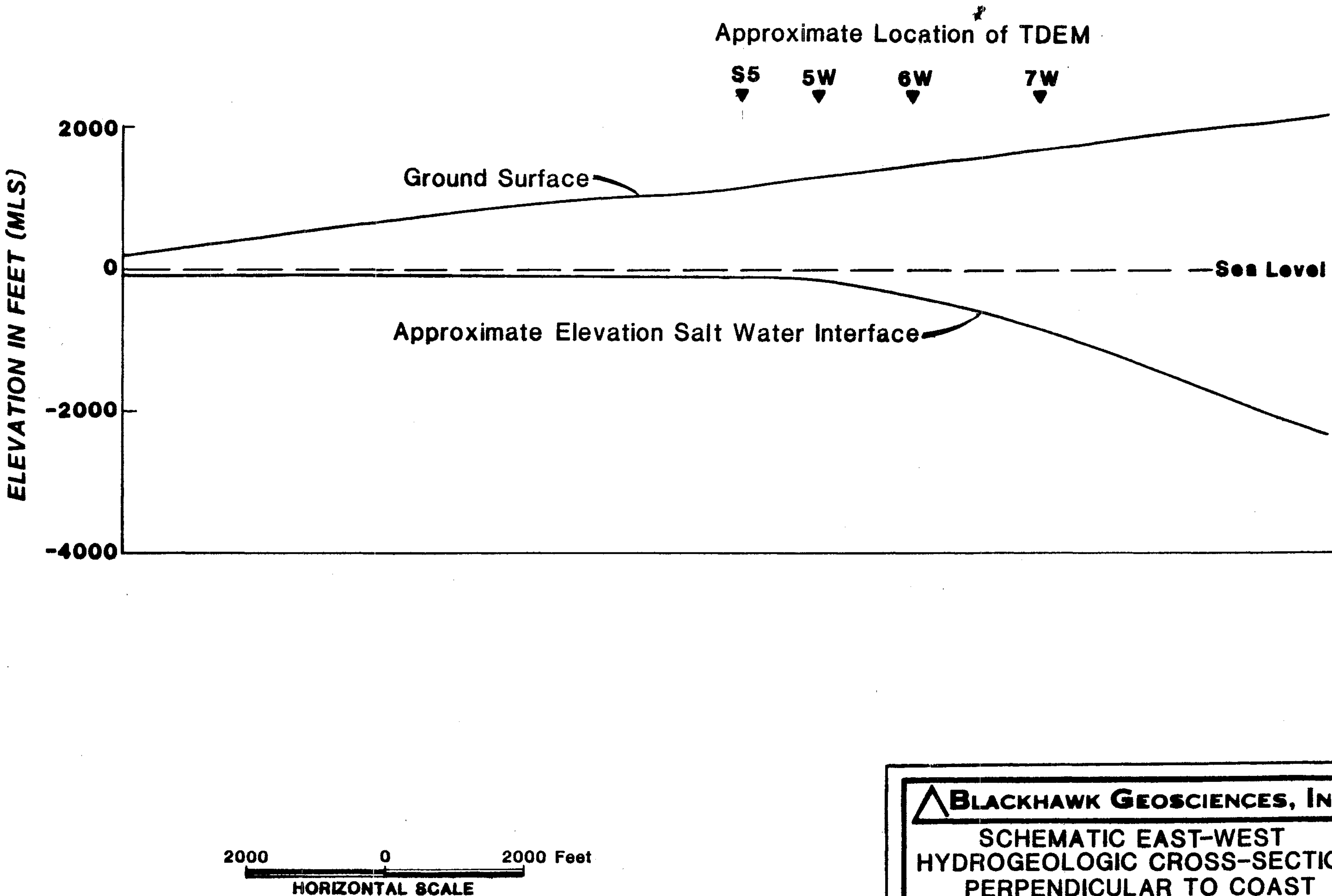
Illustration of the
Ghyben-Herzberg Principle
State of Hawaii Division of
Water Resources Management

PROJECT NO: 90042 Figure 4-1



Puu Uala
Windmill
2934
Pohakuloa
Gulch
Corral
Water Tank
Rock Walls
Keawewai
Approximate Kohala Ranch Boundary
Keanahalululu
Palapalai
Waipahoehoe
Water Tank
Corral
WT
-100
-200
-300
-400
16 -295
10 -419
9 -204
6 -272
5 R
12 R
13 R
1 R
8 R
15 R
7 R
3 R
11 C
2 C
14 C
4 C
3W C
2W C
4W -771
5W -484
8W -1000?
7W
6W
1W
#3 (150)
#1
#2 (6)
NORTH KOHALA DISTRICT
SOUTH KOHALA DISTRICT
W A I K A
H A W A I I
H U A


-98
-484
6W
-778
7W
-905
-900
-800
-700
-600
-500
-400
-300
-200
-100
S5
-75
S4
-236
S3
-291
S1
-155
S2
-239
Kawaihae Well
O #6448-01
(1)
Keawewai
Kaiopae
Gulch
Honokoa
Puu Kanane
Puu Kamalii
Gulch
LEGEND
Sounding Location
O#1 Well Number and Location
Interpreted Boundary Between Basal and Structure Controlled Water
-155 Approximate Elevation of Top of Salt Water Interface
C Conductive Basement
R Resistive Basement
(1) Static Water Level at Well (Feet)
N
HAWAIIAN ISLANDS
HAWAII
QUADRANGLE LOCATION
2000
0
2000 Feet
BLACKHAWK GEOSCIENCES, INC.
TDEM INTERPRETATION MAP
State of Hawaii Division of Water Resources Management
PROJECT NO: 90041
Figure 4-2



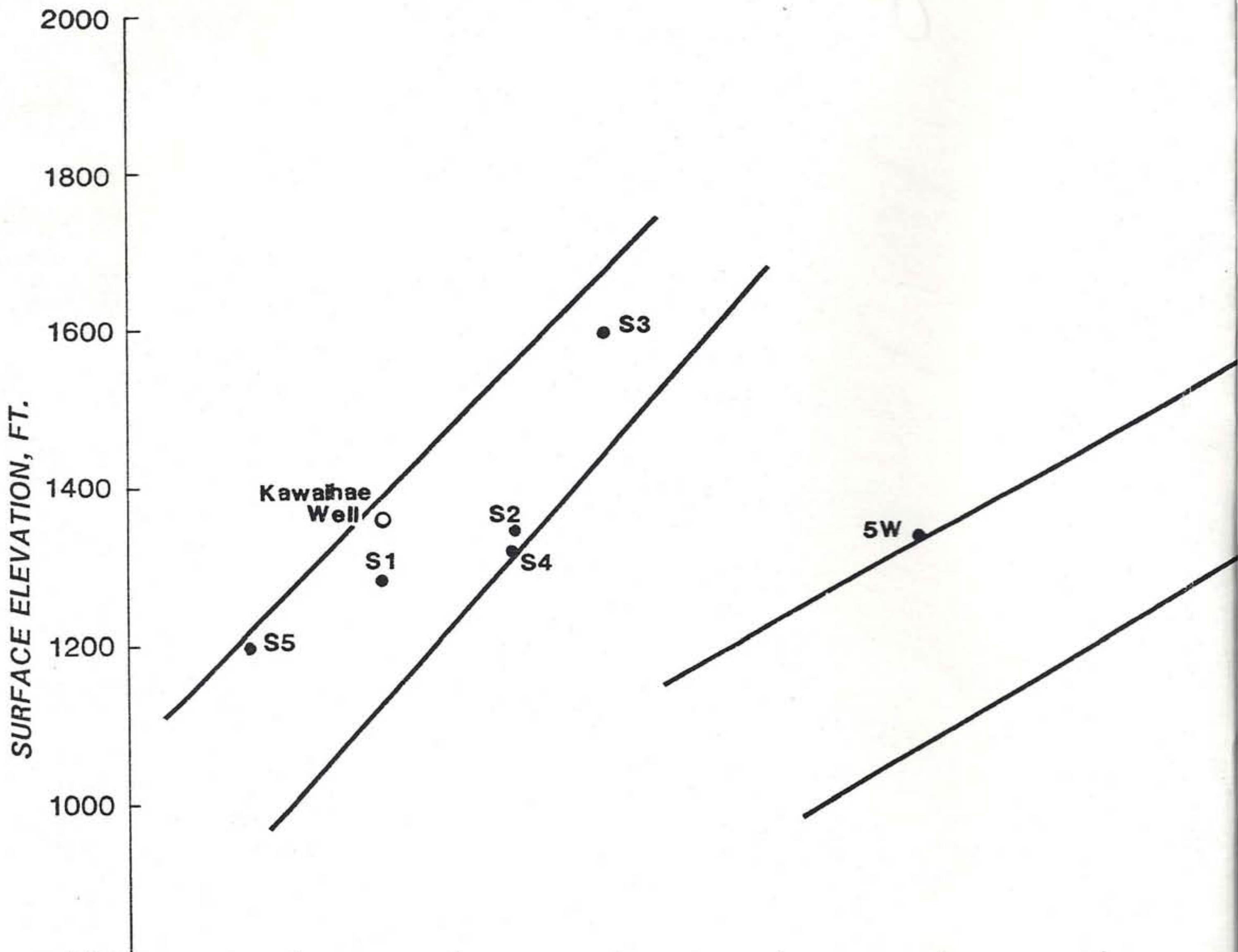
BLACKHAWK GEOSCIENCES, INC.

SCHEMATIC EAST-WEST HYDROGEOLOGIC CROSS-SECTION PERPENDICULAR TO COAST

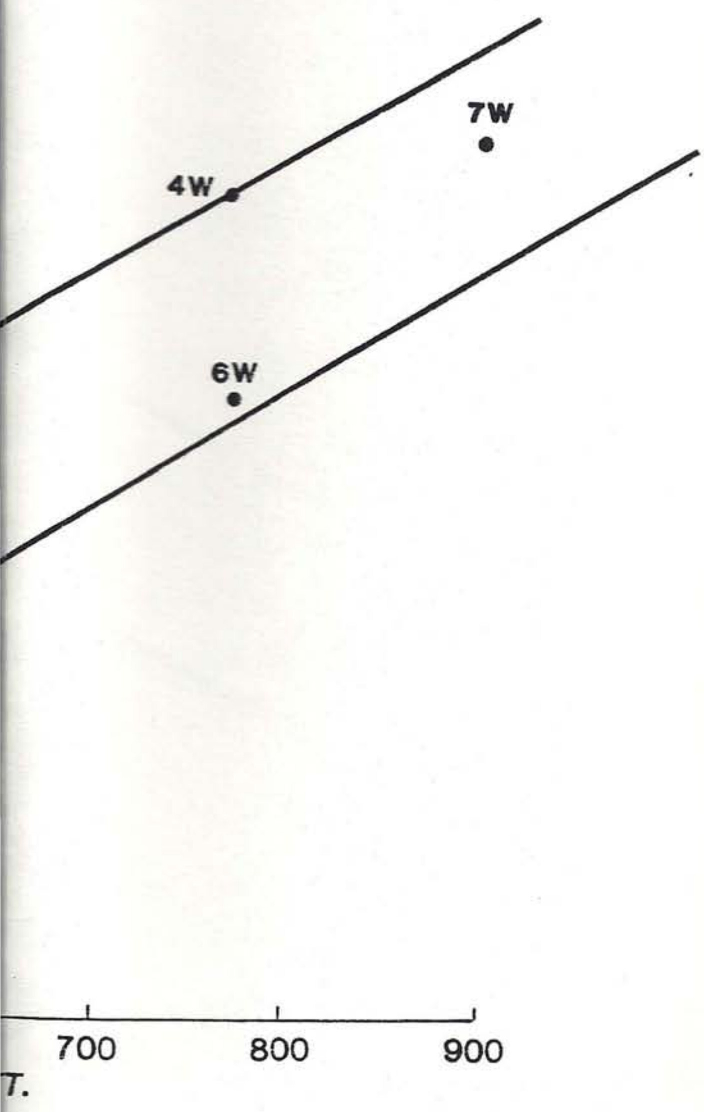
State of Hawaii Division of Water Resources Management

PROJECT NO: 90041

Figure 4-3



2000
1800
1600
1400
1200
1000
800
0
100
200
300
400
500
600
SURFACE ELEVATION, FT.
APPROXIMATE THICKNESS FRESH WATER LENS, FT.
Kawaihae
Well
S1
S2
S3
S4
S5
5W



BLACKHAWK GEOSCIENCES, INC.

SURFACE ELEVATION VS
THICKNESS FRESH WATER LENS

State of Hawaii Division of
Water Resources Management

PROJECT NO: 90041

Figure 4-4

5.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM survey was to assist in characterizing the hydrologic regime near the recently drilled Kawaihae Exploratory Well. Five soundings were made in an area around the well. The data collected for the State was combined with a data set of 24 soundings in an area mainly north of the Honokoa Gulch. The combined interpretation show several distinct zones of hydrogeologic behavior. These are:

1. Two distinct areas where ground water occurs in the basal mode. One area north of the Honokoa Gulch, and one area around the Kawaihae well.

2. A zone of structural controlled ground water. The contours suggest minor ground water flow from north to south across the boundary between areas of structurally controlled and basal ground water.

It is not possible from the TDEM survey to determine the origin and nature of the subsurface structures causing the apparent complex ground water flow regime. The main information derived from the TDEM survey is

- delineation of boundaries between areas (i) where ground water is trapped by structures, and (ii) where it occurs as a lens of fresh/brackish water floating on sea water (basal mode)

- determining approximate thickness of fresh/brackish water lens where it occurs in the basal mode.

It is likely that in this complex area TDEM surveys can further assist in resolving the ground water regime by stations east and south of the Kawaihae Exploratory Well.

PRINCIPLES OF TIME DOMAIN EM

BLACKHAWK GEOSCIENCES, INC.

Question.-- What is TDEM?

Answer.-- TDEM is a surface geophysical method for determining the lateral and vertical resistivity variation (geoelectric section) in the subsurface.

Question.-- What useful information can be derived from the geoelectric section?

Answer.-- Electrical resistivity can be used as an indicator for mapping several important objectives in the subsurface, such as:

1. Presence of contaminants. Dissolved solids in ground water decrease formation resistivities, so that industrial contaminant plumes and differences in salinity (e.g., salt water intrusion) can often be delineated from geoelectric sections.

2. Soil and rock types. Clays and clay shales, and formations of low hydraulic permeability, have lower resistivities than formations of high hydraulic permeability, such as sands and gravels, sandstones, basalts, and high porosity limestones. The geoelectric section can, therefore, be used to map continuity of clay and clay shale lenses.

3. Fractures and shear zones. Such zones are conduits for ground water flow and contaminant migration, and they are often characterized by zones of low resistivity. The reasons for the lower resistivities of these zones are infilling of the fracture zones by clay gouge, alteration of wall rock, and higher water contents.

Question.-- What advantages does TDEM have over other electrical and electromagnetic methods, such as resistivity (direct current) and electromagnetic conductivity profiling with the Geonics EM-31 and EM-34?

Answer.-- The advantages of TDEM over other electrical and electromagnetic methods are

- better vertical and lateral resolution
- lower sensitivity to geologic noise (see page 5)
- the ability to explore below highly conductive layers (e.g., brine saturated layers and clay lenses).

Some of the most frequently asked questions about TDEM and their answers are given below.

Question.-- Are the principles of TDEM similar to electromagnetic induction profiling, such as used in the Geonics EM-31 and EM-34?

Answer.-- Yes, the principles of electromagnetic induction profiling in the frequency domain (FDEM), used in the Geonics EM-31 and EM-34, are in many ways similar to the principles of TDEM.

An important difference between FDEM and TDEM is the current waveform driven through the transmitter loops. It is a continuous, harmonic-varying current in FDEM, and a half-duty cycle waveform in TDEM.

Question.-- Why does the current waveform of the transmitter make a large difference?

Answer.-- The large difference results from the fact that in FDEM the secondary magnetic field due to ground currents is measured when the transmitter current is on, and in TDEM when the transmitter current is off. In both cases the time-variant current driven through the transmitter causes a time-variant primary magnetic field. Associated with this primary magnetic field is an induced electromotive force (emf) that causes eddy current flow in the subsurface. The intensity of these currents is used to determine subsurface conductivities. The induced emf is a harmonic-varying function in FDEM and consists of narrow pulses in TDEM.

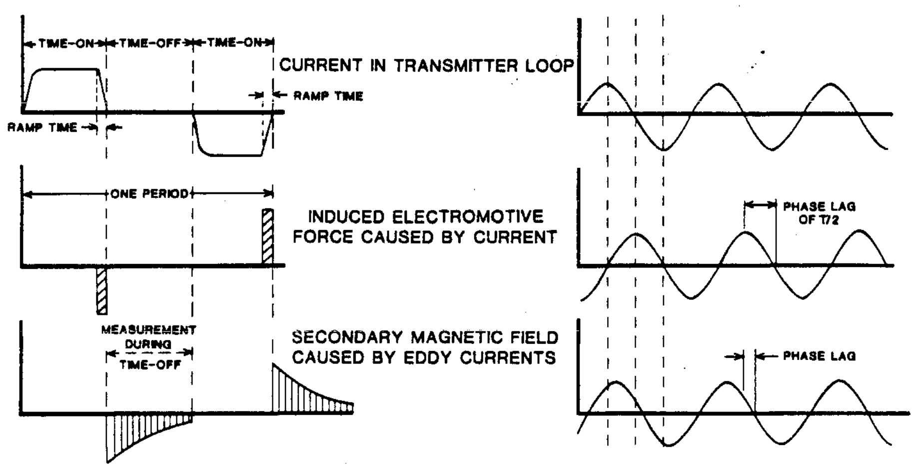


Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

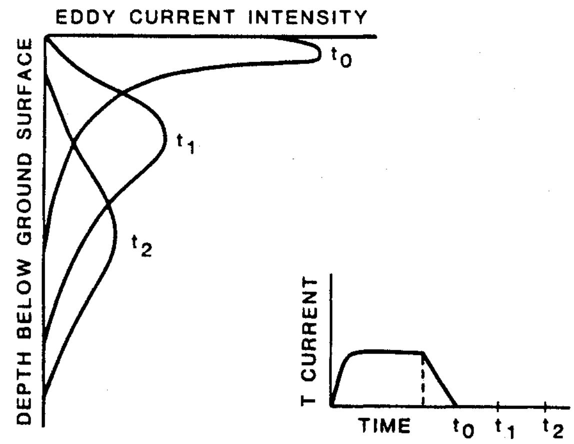


Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

Another useful presentation of distribution of current intensity as a function of time is given in Figure 4. At early time, t_0, all currents are concentrated near the surface. At later times (e.g., t_3) the current maxima occur at increasingly greater depth. Thus, from measurements of the decay of emf at one location, the geoelectric section to a substantial depth is obtained.

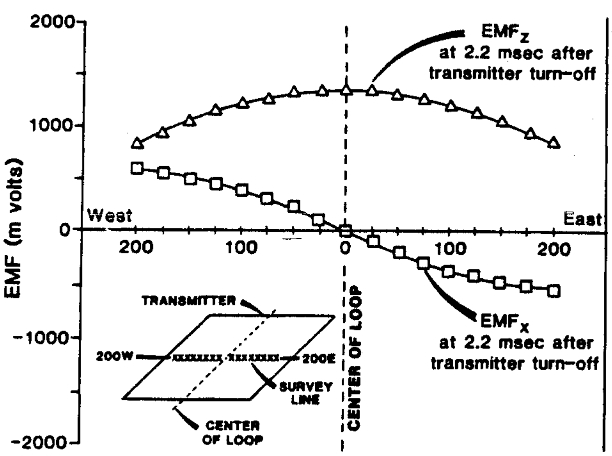


Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

The emfs caused by square transmitter loops vary with time and distance from the center. Figure 5 shows a typical measured behavior of emfs at a certain time (2.2 milliseconds) after turn-off. At other times the amplitudes will be different, but the spatial behavior is similar. The spatial behavior of the emf_z is relatively flat about the center so that measurements of emf, due to the vertical magnetic field, are relatively insensitive to errors in surveying the center of the loop, or to deviations from a square loop. This is clearly of practical value because it (1. reduces the cost of land surveys and measurement errors, and (2) allows for some flexibility in the field in positioning the measurement stations.

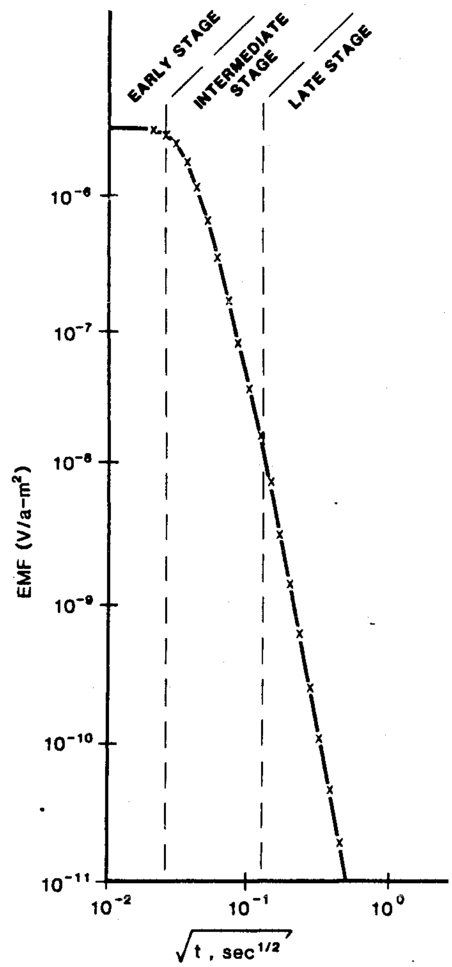


Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

Thus, in TDEM soundings, the geoelectric section is derived from measurement of the emf due to the vertical magnetic field (emf_z) as a function of time during the period the transmitter is off. Figure 6 shows a typical behavior of emf_z as a function of time. Emf_z can be seen to decay rapidly with increasing time. One transient decay recorded over a few tens of milliseconds contains information about resistivity layering over a significant depth range.

The emfs, due to the decay of the ground eddy currents, must be measured in the presence of ambient noise sources, such as geomagnetic storms, lightning, 60 hertz powerlines, and other man-made sources. It is common to stack several hundred transient decays to improve signal to noise. Stacking of several hundred transient decays requires only a few seconds, and multiple data sets can be quickly obtained.

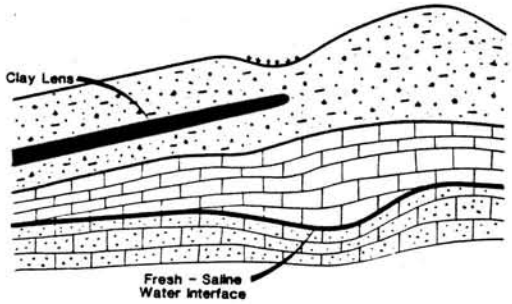


Fig. 9. Schematic geologic section of Floridan aquifer.

Question.-- How does TDEM reduce geologic noise?

Answer.-- This fact can be conceptually explained from Figure 10 where the intensity of eddy current distribution is schematically illustrated as a function of time for the FDEM and TDEM method. At early time (t_0) in TDEM all currents are concentrated near the surface, and near surface formations will largely determine the emf measured. At later time, for example, t_3, currents have largely decayed in near surface layers, and currents dominantly flow at greater depth. The emf measured at time t_3 is near transparent to near surface layers, so that their influence is greatly reduced at time t_3 and later times.

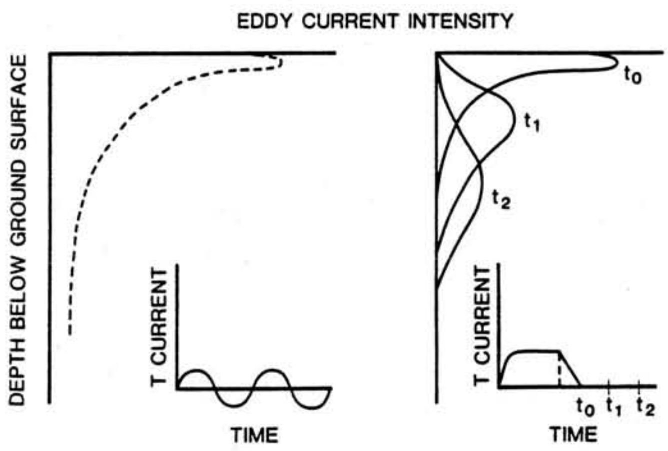


Fig. 10. Eddy current intensity in FDEM and TDEM.

In the FDEM method current intensity is always highest near the surface amplifying the influence of near surface layers.

In summary, geologic noise due to lateral and vertical resistivity variation in TDEM is reduced because:

(a) Exploration depth is mainly a function of time rather than transmitter-receiver separation. The transmitter-receiver separation need not be altered to change exploration depth as is the case in FDEM (EM-31 and EM-34), and direct current resistivity methods.

(b) Relatively small transmitter-receiver separations compared to effective exploration depth are employed.

(c) Measurements at later times are nearly transparent to near surface layers, because eddy currents at later times dominantly flow at greater depth.

Question.-- Can TDEM surveys be effective in mapping fractures and shear zones?

Answer.-- Yes, TDEM can detect contacts, fractures, and shear zones below considerable overburden thickness. The physical concepts of fracture and shear zone mapping are briefly explained.

Electrical and electromagnetic methods are often effective in mapping fractures and shear zones, because fractures and shear zones often are zones of low resistivity in more resistive host rocks. These lower resistivities are generally caused by clay gouge, higher water contents, and alteration in wall rocks. The mapping of fractures and shear zones becomes increasingly more difficult with increasing overburden thickness where outcrops are limited. It is in these situations that geophysical surveys can play an important role.

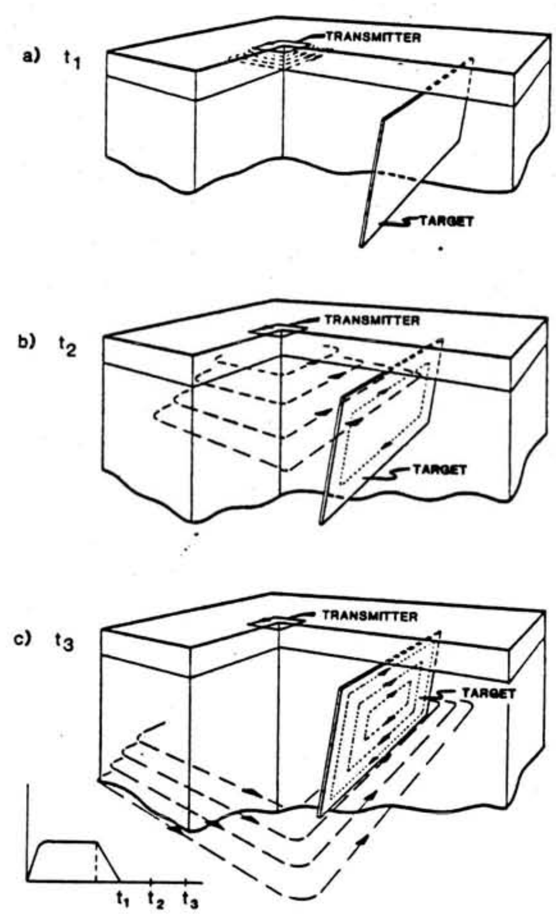


Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

Measurements at the same location were made with TDEM in 200 m by 200 m transmitter loops, and the results of central-loop TDEM soundings are shown in Figure 14. Again, the measured apparent resistivity curves are superimposed on three forward model curves, and the geoelectric sections of the three model curves are shown on the right. Depth to bedrock in the models is varied by 20 m. It is evident that vertical resolution of determining depth to bedrock is now ± 10 m.

Thus, not only was the physical effort required to sound to a depth of 168 m greatly reduced - only 800 m (4 x 200 m) of wire needed to be laid out, - but the vertical resolution was greatly improved.

Question.-- Summarize for me the potential of TDEM in environmental and ground water geophysics.

Answer.--Electrical surface geophysical methods are an important tool because (1) electrical resistivity is the only readily measureable physical property highly dependent of concentration of dissolved solids (water quality), and (2) electrical resistivity often closely relates to clay content and hydraulic permeability. In the past the vertical and lateral resolution of electrical methods was poor. TDEM techniques are changing that reputation.

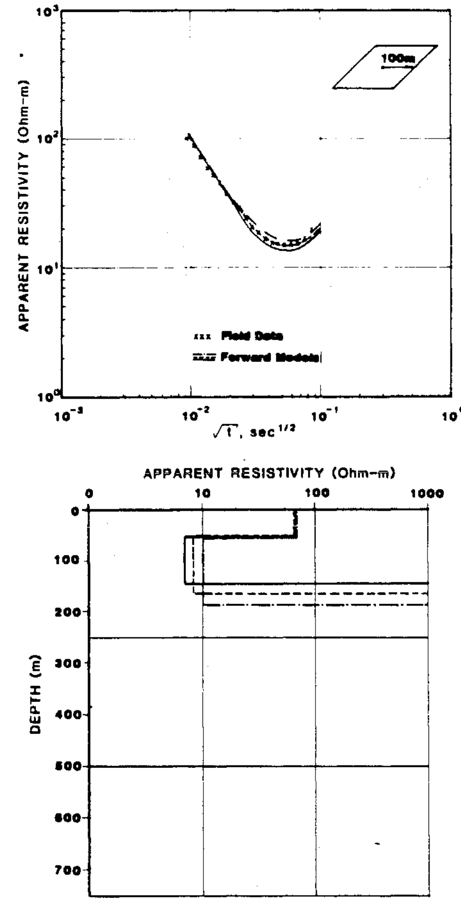
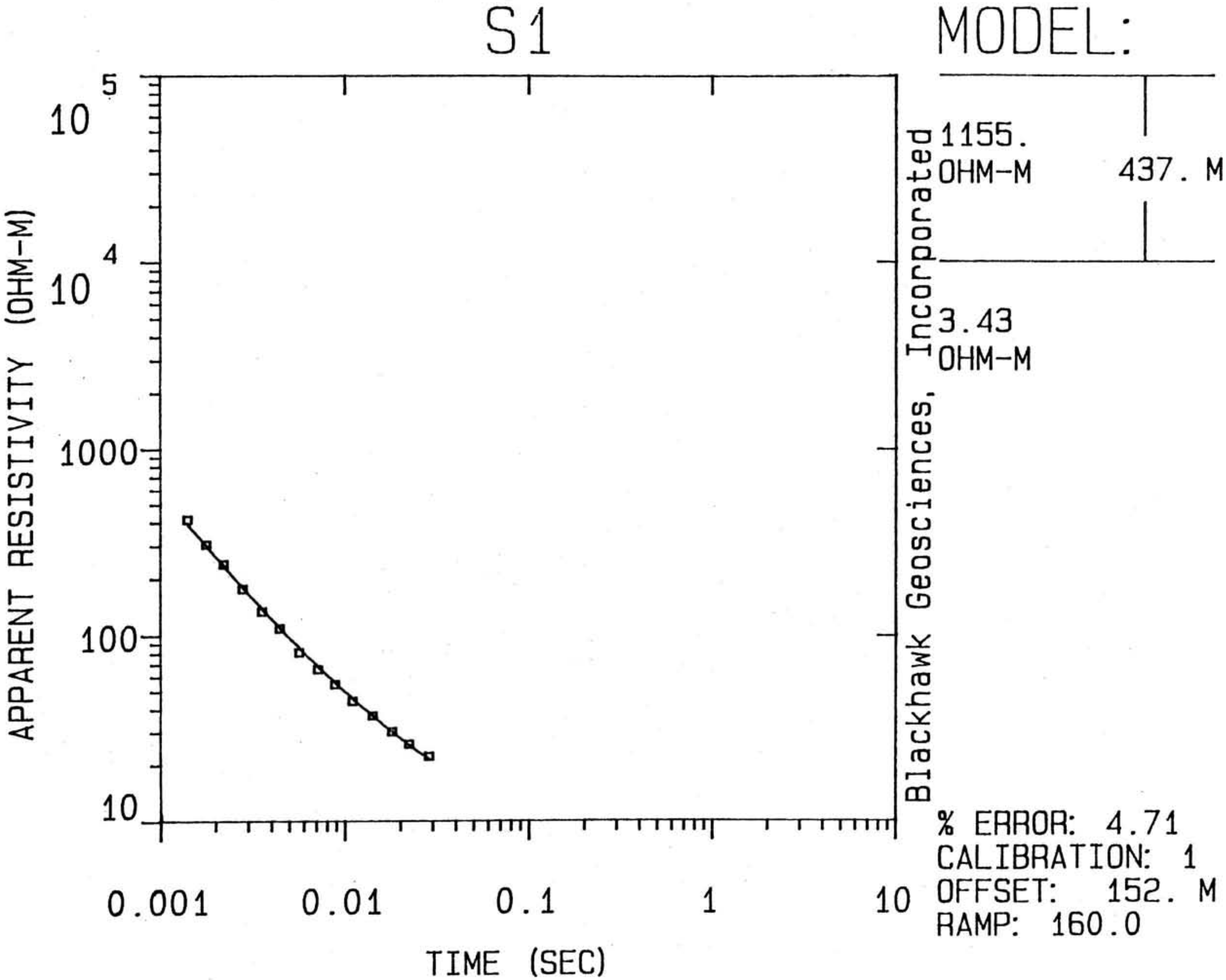


Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.



S1
MODEL:
1155.
OHM-M
437. M
3.43
OHM-M
Blackhawk Geosciences, Incorporated
% ERROR: 4.71
CALIBRATION: 1
OFFSET: 152. M
RAMP: 160.0
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
0.001
0.01
0.1
1
10
TIME (SEC)

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		390.1	1280.0		
1155.34	437.4	-47.3	-155.0	0.4	0.4
3.43					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.40E-03	4.13E+02	3.89E+02	6.222	
2	1.77E-03	3.04E+02	2.97E+02	2.472	
3	2.20E-03	2.38E+02	2.32E+02	2.409	
4	2.80E-03	1.76E+02	1.78E+02	-1.003	
5	3.55E-03	1.34E+02	1.38E+02	-2.964	
6	4.43E-03	1.09E+02	1.09E+02	-0.463	
7	5.64E-03	8.09E+01	8.53E+01	-5.152	
8	7.13E-03	6.54E+01	6.77E+01	-3.387	
9	8.81E-03	5.44E+01	5.54E+01	-1.842	
10	1.10E-02	4.42E+01	4.55E+01	-2.809	
11	1.41E-02	3.68E+01	3.65E+01	0.744	
12	1.80E-02	3.01E+01	3.00E+01	0.365	
13	2.22E-02	2.58E+01	2.54E+01	1.838	
14	2.85E-02	2.21E+01	2.12E+01	4.360	

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RMS LOG ERROR: 2.00E-02, ANTILOG YIELDS 4.7135 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

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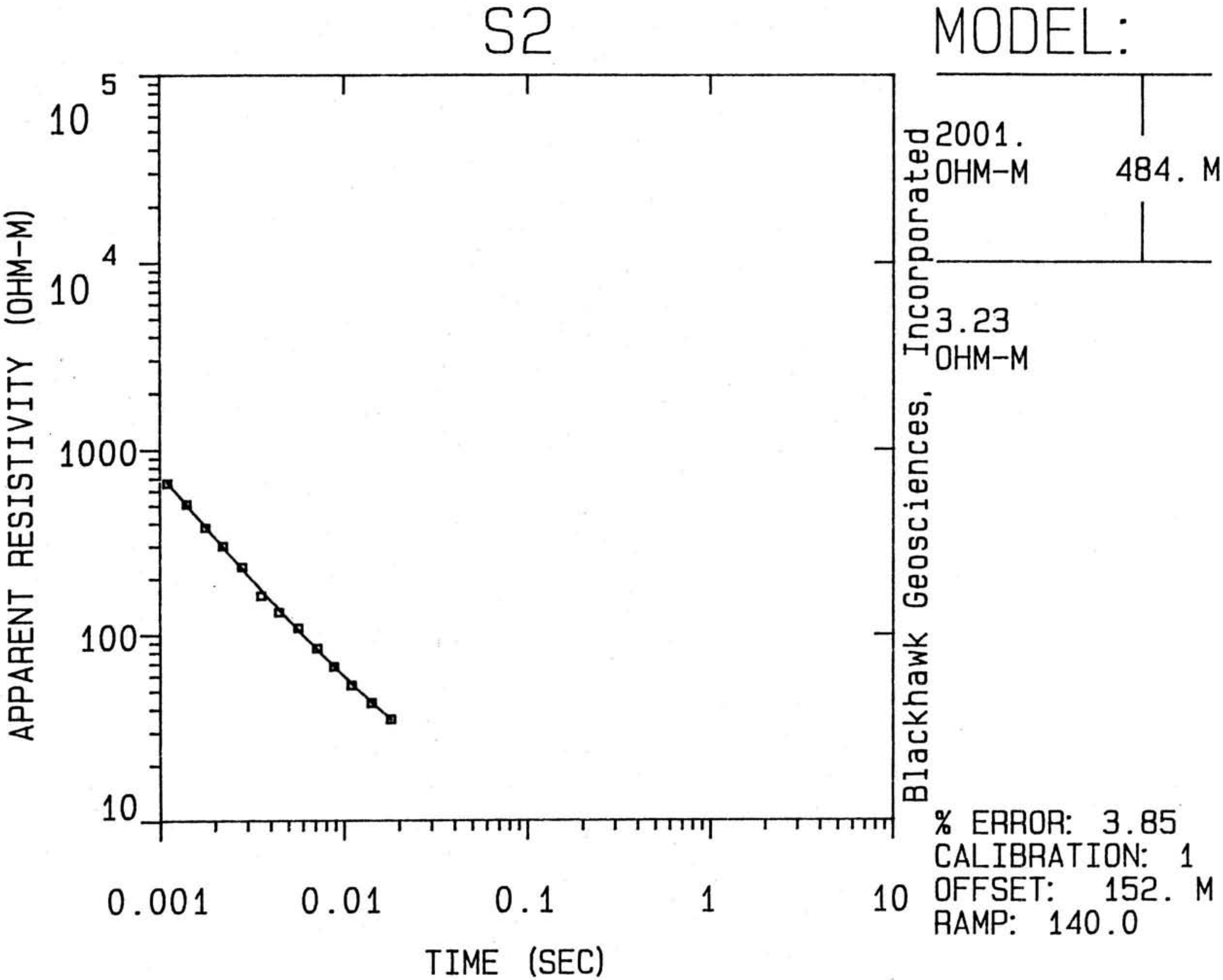
P 2	-0.04	0.93	
T 1	0.01	0.00	1.00
	P 1	P 2	T 1


S2
MODEL:
2001.
OHM-M
484. M
3.23
OHM-M
Blackhawk Geosciences, Incorporated
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
0.001
0.01
0.1
1
10
TIME (SEC)
% ERROR: 3.85
CALIBRATION: 1
OFFSET: 152. M
RAMP: 140.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		411.5	1350.0		
2001.20	484.3	-72.8	-238.9	0.2	0.2
3.23					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-03	6.58E+02	6.65E+02	-1.107	
2	1.40E-03	5.06E+02	4.98E+02	1.581	
3	1.77E-03	3.78E+02	3.78E+02	-0.148	
4	2.20E-03	2.99E+02	2.94E+02	1.654	
5	2.80E-03	2.30E+02	2.24E+02	3.057	
6	3.55E-03	1.61E+02	1.72E+02	-6.366	
7	4.43E-03	1.31E+02	1.35E+02	-2.689	
8	5.64E-03	1.08E+02	1.05E+02	3.004	
9	7.13E-03	8.40E+01	8.24E+01	1.847	
10	8.81E-03	6.72E+01	6.69E+01	0.450	
11	1.10E-02	5.33E+01	5.43E+01	-1.895	
12	1.41E-02	4.31E+01	4.31E+01	-0.152	
13	1.80E-02	3.52E+01	3.50E+01	0.511	

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Ch.21 = 0.14 Ch.22 = 0.89 Ch.23 = 14 Ch.24 = 92
RMS LOG ERROR: 1.64E-02, ANTILOG YIELDS 3.8493 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

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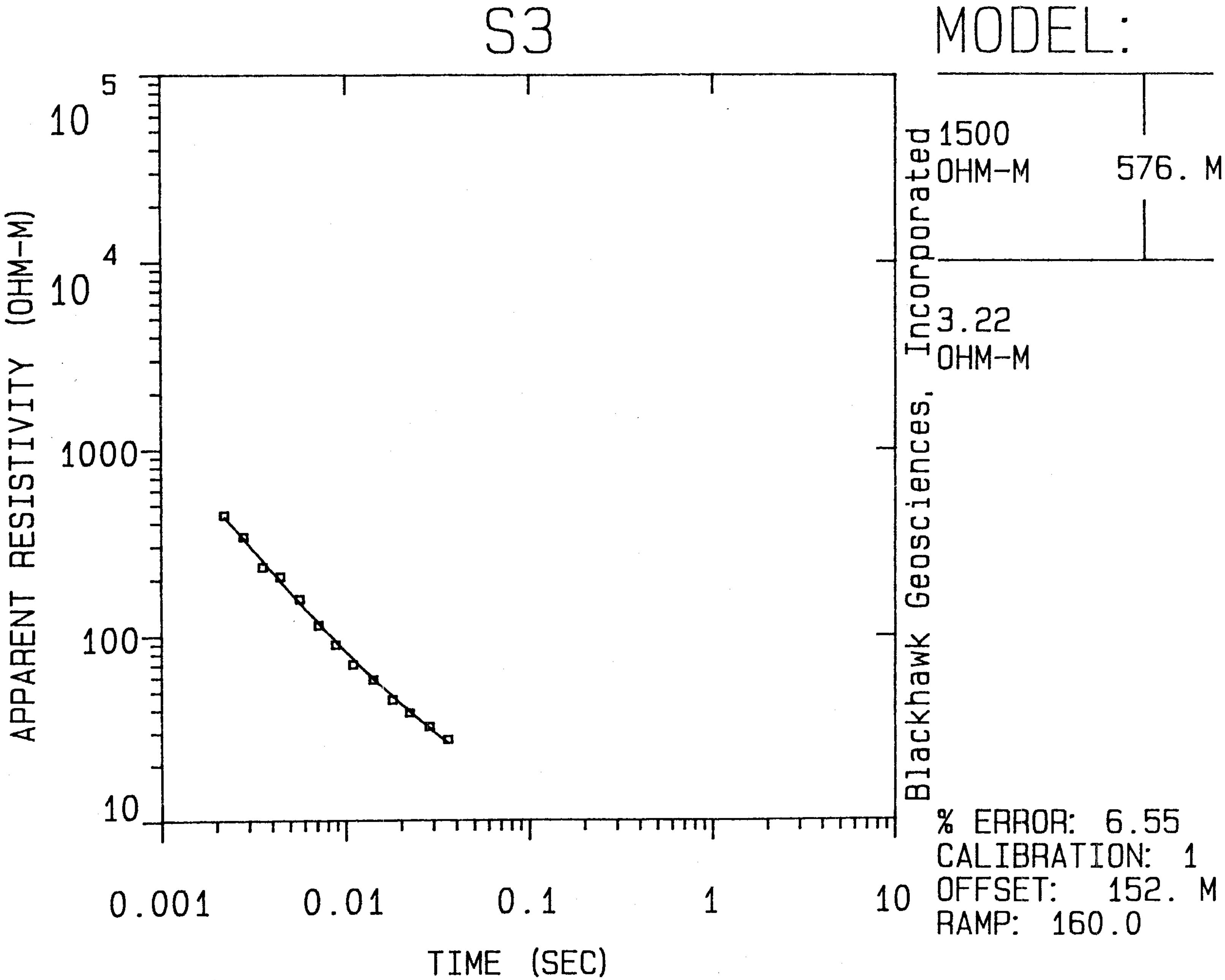
P 2	-0.04	0.99	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

S3


MODEL:
1500
OHM-M
576. M
3.22
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
0.001
0.01
0.1
1
10
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 6.55
CALIBRATION: 1
OFFSET: 152. M
RAMP: 160.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		487.7	1600.0		
1500.00	576.3	-88.7	-290.9	0.4	0.4
3.22					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.20E-03	4.42E+02	4.31E+02	2.549	
2	2.80E-03	3.37E+02	3.26E+02	3.432	
3	3.55E-03	2.32E+02	2.49E+02	-6.734	
4	4.43E-03	2.06E+02	1.94E+02	6.216	
5	5.64E-03	1.57E+02	1.49E+02	5.211	
6	7.13E-03	1.14E+02	1.16E+02	-1.648	
7	8.81E-03	9.00E+01	9.35E+01	-3.746	
8	1.10E-02	7.05E+01	7.51E+01	-6.105	
9	1.41E-02	5.84E+01	5.88E+01	-0.732	
10	1.80E-02	4.53E+01	4.71E+01	-3.685	
11	2.22E-02	3.85E+01	3.89E+01	-1.144	
12	2.85E-02	3.24E+01	3.16E+01	2.638	
13	3.60E-02	2.75E+01	2.62E+01	5.035	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
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Ch.21 = 0.16 Ch.22 = 0.89 Ch.23 = 15 Ch.24 = 92
RMS LOG ERROR: 2.75E-02, ANTILOG YIELDS 6.5473 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

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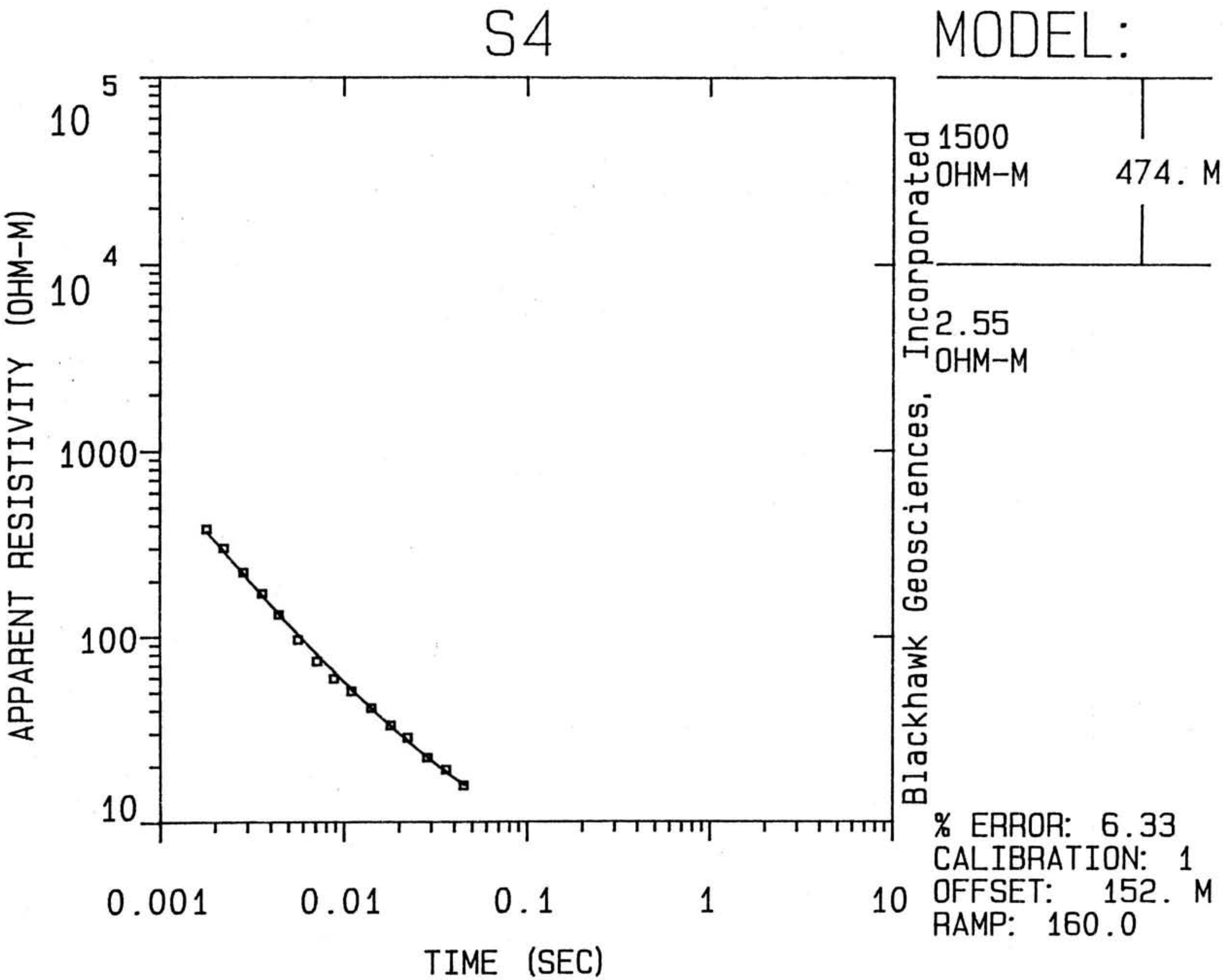
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	F 1	P 2	T 1


S4
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
0.001
0.01
0.1
1
10
TIME (SEC)
1500
OHM-M
474. M
2.55
OHM-M
Blackhawk Geosciences, Incorporated
% ERROR: 6.33
CALIBRATION: 1
OFFSET: 152. M
RAMP: 160.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		402.3	1320.0		
1500.00	474.2	-71.9	-235.8	0.3	0.3
2.55					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.80E-03	3.81E+02	3.69E+02	3.446	
2	2.22E-03	3.01E+02	2.87E+02	4.878	
3	2.85E-03	2.22E+02	2.16E+02	3.099	
4	3.60E-03	1.71E+02	1.66E+02	3.250	
5	4.43E-03	1.31E+02	1.32E+02	-0.107	
6	5.64E-03	9.58E+01	1.01E+02	-5.604	
7	7.13E-03	7.32E+01	7.94E+01	-7.711	
8	8.81E-03	5.91E+01	6.40E+01	-7.597	
9	1.10E-02	5.05E+01	5.16E+01	-2.205	
10	1.41E-02	4.11E+01	4.06E+01	1.139	
11	1.80E-02	3.30E+01	3.27E+01	1.036	
12	2.22E-02	2.84E+01	2.72E+01	4.652	
13	2.85E-02	2.23E+01	2.22E+01	0.414	
14	3.60E-02	1.91E+01	1.85E+01	3.080	
15	4.49E-02	1.57E+01	1.58E+01	-0.486	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
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Ch.21 = 0.16 Ch.22 = 0.089 Ch.23 = 14 Ch.24 = 9
RMS LOG ERROR: 2.67E-02, ANTILOG YIELDS 6.3333 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

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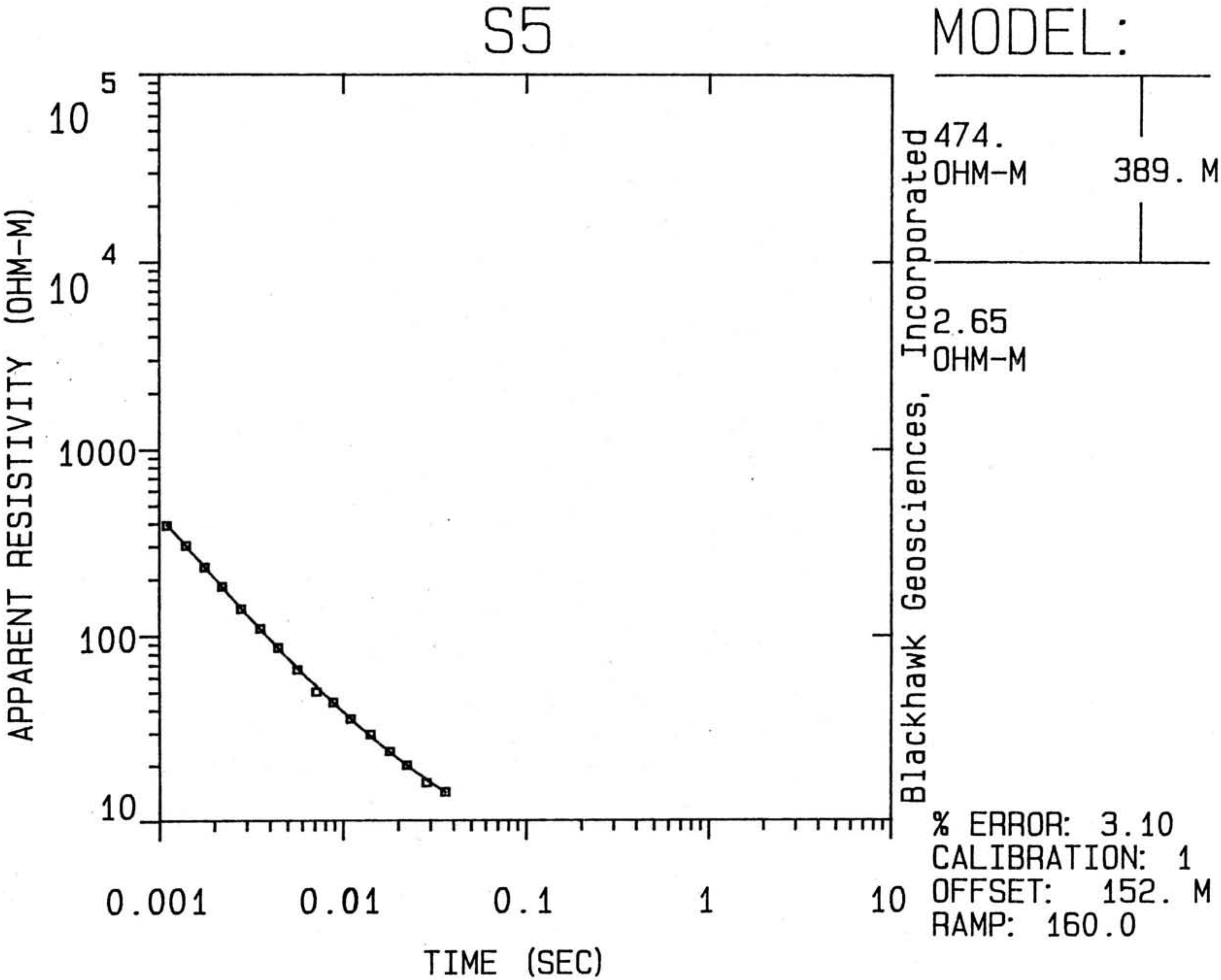
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	F 1	P 2	T 1


S5
MODEL:
10^5
10^4
1000
100
10
APPARENT RESISTIVITY (OHM-M)
0.001
0.01
0.1
1
10
TIME (SEC)
Blackhawk Geosciences, Incorporated
474.
OHM-M
389. M
2.65
OHM-M
% ERROR: 3.10
CALIBRATION: 1
OFFSET: 152. M
RAMP: 160.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		365.8	1200.0		
474.49	388.5	-22.8	-74.7	0.8	0.8
2.65					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-03	3.91E+02	3.96E+02	-1.242	
2	1.40E-03	3.04E+02	3.01E+02	0.984	
3	1.77E-03	2.33E+02	2.31E+02	0.662	
4	2.20E-03	1.83E+02	1.81E+02	1.006	
5	2.80E-03	1.39E+02	1.39E+02	-0.107	
6	3.55E-03	1.10E+02	1.08E+02	1.472	
7	4.43E-03	8.65E+01	8.57E+01	0.900	
8	5.64E-03	6.61E+01	6.71E+01	-1.527	
9	7.13E-03	5.03E+01	5.33E+01	-5.602	
10	8.81E-03	4.41E+01	4.36E+01	1.081	
11	1.10E-02	3.58E+01	3.58E+01	0.197	
12	1.41E-02	2.95E+01	2.87E+01	2.789	
13	1.80E-02	2.39E+01	2.35E+01	1.423	
14	2.22E-02	2.01E+01	1.99E+01	0.897	
15	2.85E-02	1.61E+01	1.66E+01	-3.248	
16	3.60E-02	1.43E+01	1.41E+01	1.099	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
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Ch.21 = 0.16 Ch.22 = 0.089 Ch.23 = 14 Ch.24 = 9
RMS LOG ERROR: 1.32E-02, ANTILOG YIELDS 3.0974 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

	P 1	P 2	T 1
P 1	0.79		
P 2	-0.02	1.00	
T 1	0.00	0.00	1.00

GEOPHYSICAL SURVEY
GROUND WATER EVALUATION
KOHALA RANCH
ISLAND OF HAWAII

GEOPHYSICAL SURVEY
GROUND WATER EVALUATION
KOHALA RANCH, ISLAND OF HAWAII

Prepared For:

Kohala Joint Venture
737 Bishop Street, Suite 2775
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Prepared By:

Blackhawk Geosciences, Inc.
17301 West Colfax Avenue, Suite 170
Golden, CO 80401

May 18, 1990

(Our Project #90016)

Table of Contents

EXECUTIVE SUMMARY

A surface geophysical survey was conducted at the Kohala Ranch Development between March 26 and April 25, 1990 for the purpose of assisting in mapping ground water resources.

Ground water resources in geologic settings, such as that found on the Kohala Ranch Development, are of two types:

(1) Basal fresh water where a lens of fresh water floats on sea water, and the elevation of the interface can be described by the Ghyben-Herzberg equation. This equation states that for every foot of fresh water head above mean sea level, 40 ft of fresh water is expected below sea level.

(2) Dike-confined water where geological structures such as intrusive rock bodies and dikes control the ground water regime. Fresh water heads in these areas are controlled by many factors, and can be highly variable.

At the Kohala Ranch both types of water resources occur and the geophysical surveys outlined boundaries between these types of hydrological provinces. In areas of basal fresh water occurrences the thickness of lenses of fresh water were computed. In areas of dike-confined water, areas of similarity in geophysical responses and expected hydrology were outlined.

1.0 INTRODUCTION

This report contains the results of a geophysical survey for ground water resource evaluation at the Kohala Ranch Development (KRD) on the Island of Hawaii. The work was performed by Blackhawk Geosciences, Inc. (BGI) for Kohala Joint Venture during March 26 to April 26, 1990.

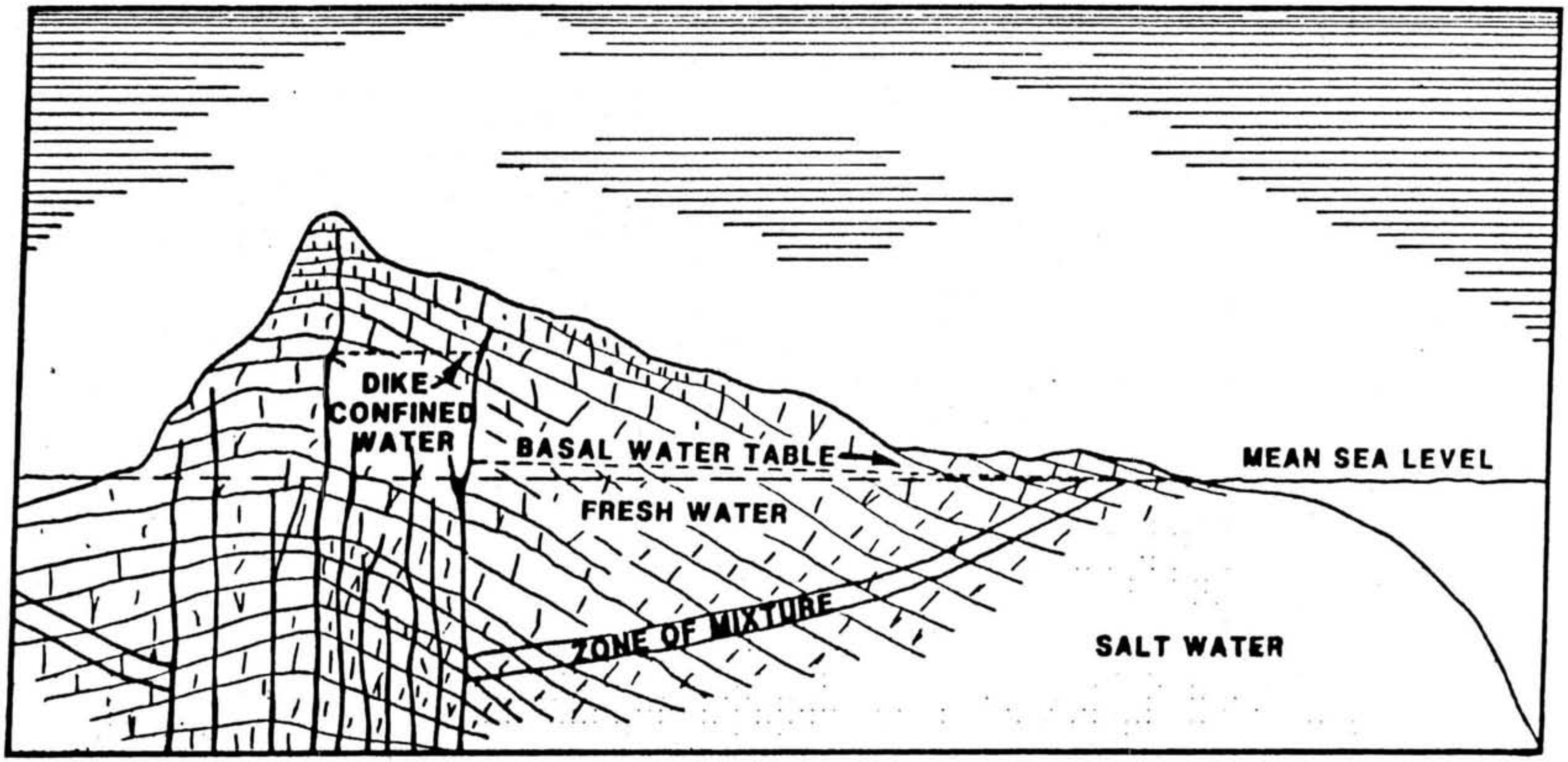
The general objective of the geophysical survey at KRD was to assist in characterizing the hydrologic regime in the study area. Recent drilling results revealed abnormally high static water levels in a well on the property, and the geophysical survey was performed to attempt to map the extent and cause of this anomaly. The generalized objectives for geophysical surveys for ground water evaluations on volcanic islands are illustrated in Figure 1-1. The volcanic rocks are generally highly permeable and this allows rainwater to percolate with little impedance directly downward through the island mass. The fresh water in these island settings is generally found in two environments:

1. <u>Dike-confined waters</u>. Typically, above the rift zone, intrusive dikes originating from a magma source below can form ground water dams, and behind these natural dams significant quantities of ground water can be stored.

2. <u>Basal fresh water</u>. The high permeability of the volcanic rocks allows sea water to enter freely under the island, and a delicate balance is reached where a lens of fresh water floats on sea water. In cases of hydrostatic equilibrium, the Ghyben-Herzberg relation states that for every foot of fresh water head above sea level there will be 40 ft of fresh water below sea level.

At KRD both dike-confined and basal fresh water resources were indicated due to the large variation in static water levels at the various wells within the development (well #3 ≈ 150 ft, wells #1 and #2 ≈ 6 ft). The impetus for using geophysics is that the cost of a geophysical station is about one-thousandth the cost of completing a well at elevations above 1,000 ft. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and well completion depths.

The geophysical method employed was time domain electromagnetic (TDEM) soundings. This method was selected because it has proven effective in prior surveys in similar settings in Hawaii.



BLACKHAWK GEOSCIENCES, INC.

SCHEMATIC HYDRO-GEOLOGIC CROSS SECTION

KOHALA RANCH PROJECT

NORTH KOHALA, HAWAII

PROJECT NO.: 90016

FIGURE 1-1

2.0 LOGISTICS AND DATA ACQUISITION

A brief description of the fundamentals of TDEM are given in Appendix A. Briefly, the logistics of a TDEM measurement consist of:

1. Laying out a square loop of insulated wire. A generator placed in the loop is used to drive current pulses through this closed loop. The dimensions of the square loops employed depend on the exploration depth requirements. The dimensions of the loops used for KRD were 1,000 ft by 1,000 ft on each side for all loops, with the exception of loop 1W where a 500 ft by 500 ft transmitter loop was used.

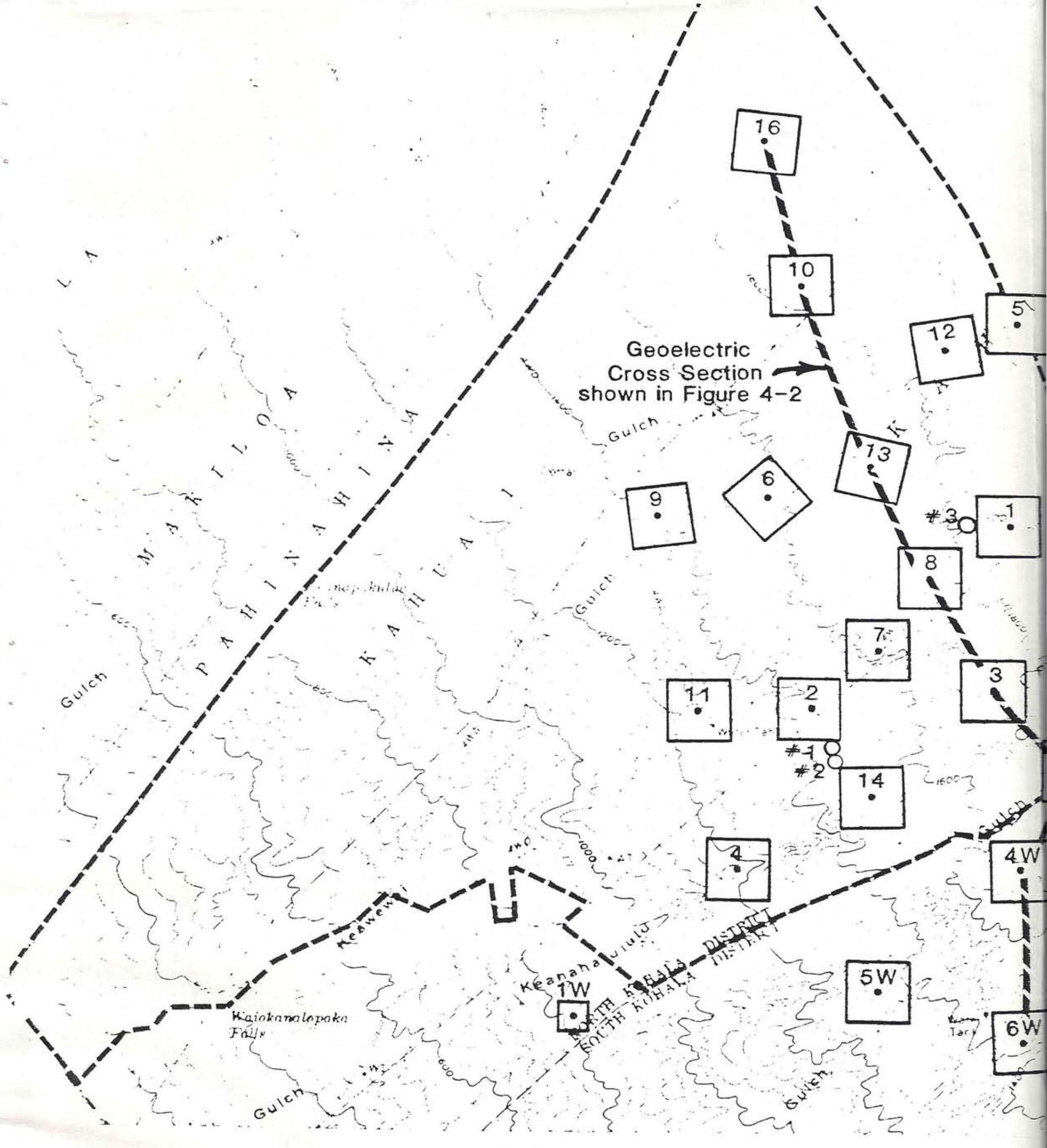
   Transmitter loop wires were positioned so as not to cross utility lines. Soundings 1, 2 and 1W were positioned near wells.

2. Making a measurement with a receiver in the center of the loop. The data acquired at each station was stored in the field on a solid state data logger and subsequently dumped to a computer at the end of each field day. The data acquired at each station usually consisted of measurements at several receiver gain settings and transmitter frequencies in order to assure data quality and to obtain data over the largest time range possible. Data quality was generally very good.

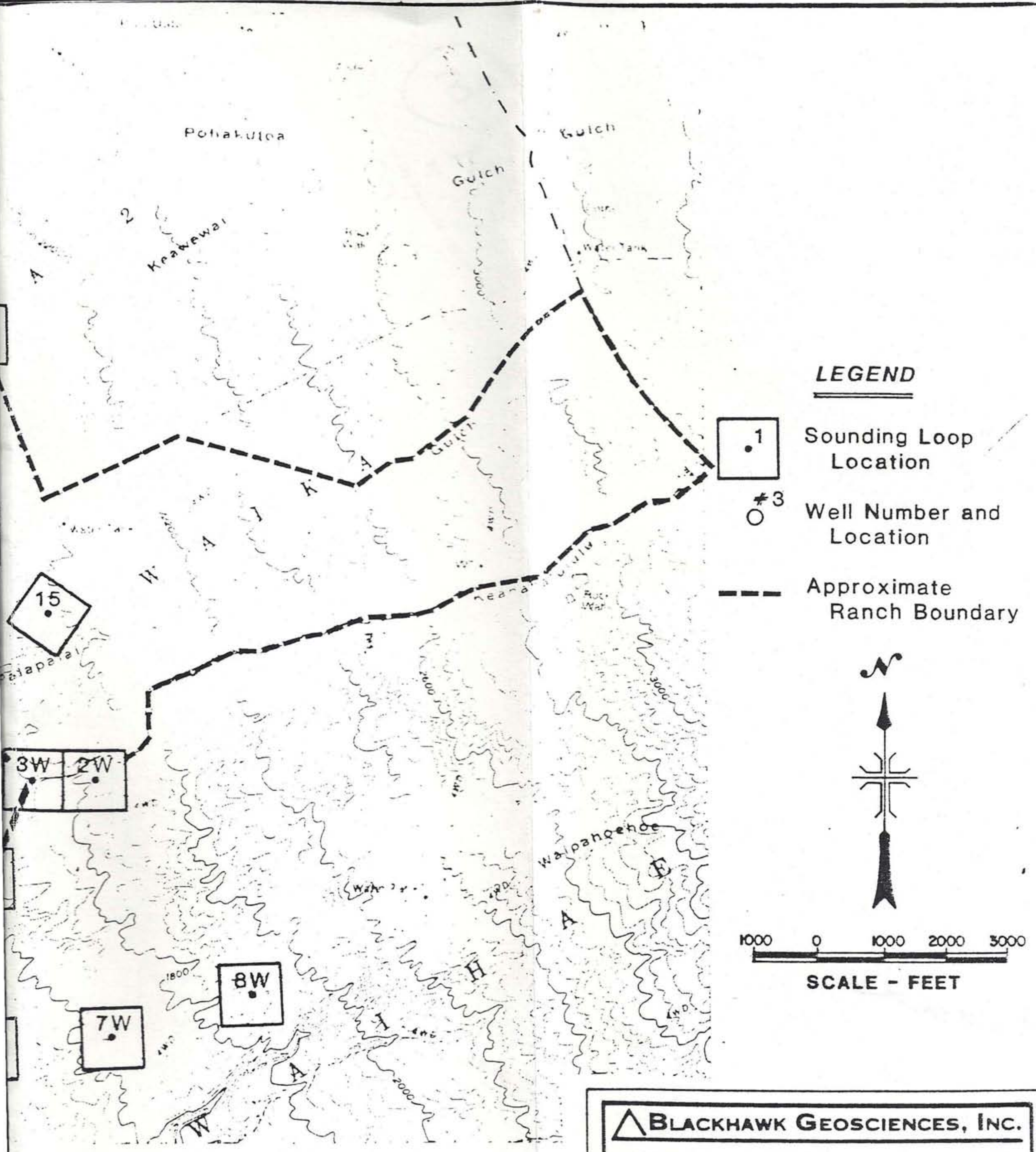
During the 8 days of field work 24 stations (soundings) were completed. A daily log of field activity is given in Table 2-1. Figure 2-1 shows the location of the soundings conducted for KRD.

Table 2-1. Daily log of field activities

Date (1990)	Activity
March 26	BGI personnel mobilize from Golden, CO to Kailua-Kona, Hawaii in conjunction with the other surveys.
April 5	Meet with KRD personnel and check survey areas.
April 6	Soundings 1, 2 and 3.
April 7	Soundings 4, 5 and 6.
April 8	Soundings 7, 8, 9 and 10.
April 9	Soundings 11, 12 and 13.
April 10	Soundings 14, 15 and 16.
April 11-12	Demobilize to Golden, CO and perform preliminary analysis of data.
April 18	Mobilize to Kailua-Kona, Hawaii.
April 23	Soundings 1W, 2W and 3W.
April 24	Soundings 4W, 5W and 6W.
April 25	Soundings 7W and 8W.
April 26	Demobilize to other Hawaii geophysical surveys.



16
10
5
12
Geoelectric
Cross Section
shown in Figure 4-2
13
6
9
#3
1
8
7
3
11
2
#1
#2
14
4
4W
5W
1W
6W
Gulch
Keawewai
Keanahaaulu
NORTH KOHALA DISTRICT
SOUTH KOHALA DISTRICT
Waiokanalopaka Falls
PAHINAHINA
MAKILOA
KAHUA 1



BLACKHAWK GEOSCIENCES, INC.

TDEM SURVEY LOCATION MAP

KOHALA RANCH PROJECT
NORTH KOHALA, HAWAII

PROJECT NO.: 90016

FIGURE 2-1

3.0 DATA PROCESSING

The field data acquired each day was transferred from the DAS-54 data logger to a Compaq computer. The data for each sounding location is edited and combined (both 3 Hz and 30 Hz frequencies) to produce a transient decay curve. This decay curve is transformed into an apparent resistivity curve, which is entered into an Automatic Ridge Regression Transient Inversion Program (ARRTI). From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers, and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to float freely.

An example data set is given in Figures 3-1 and 3-2 for sounding KR1. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed behavior of the true resistivity layering shown on the right. Figure 3-2 lists in column 4 the error between measured and computed data in each time gate.

The apparent resistivity curves and data sheets for all soundings are contained in Attachment A.

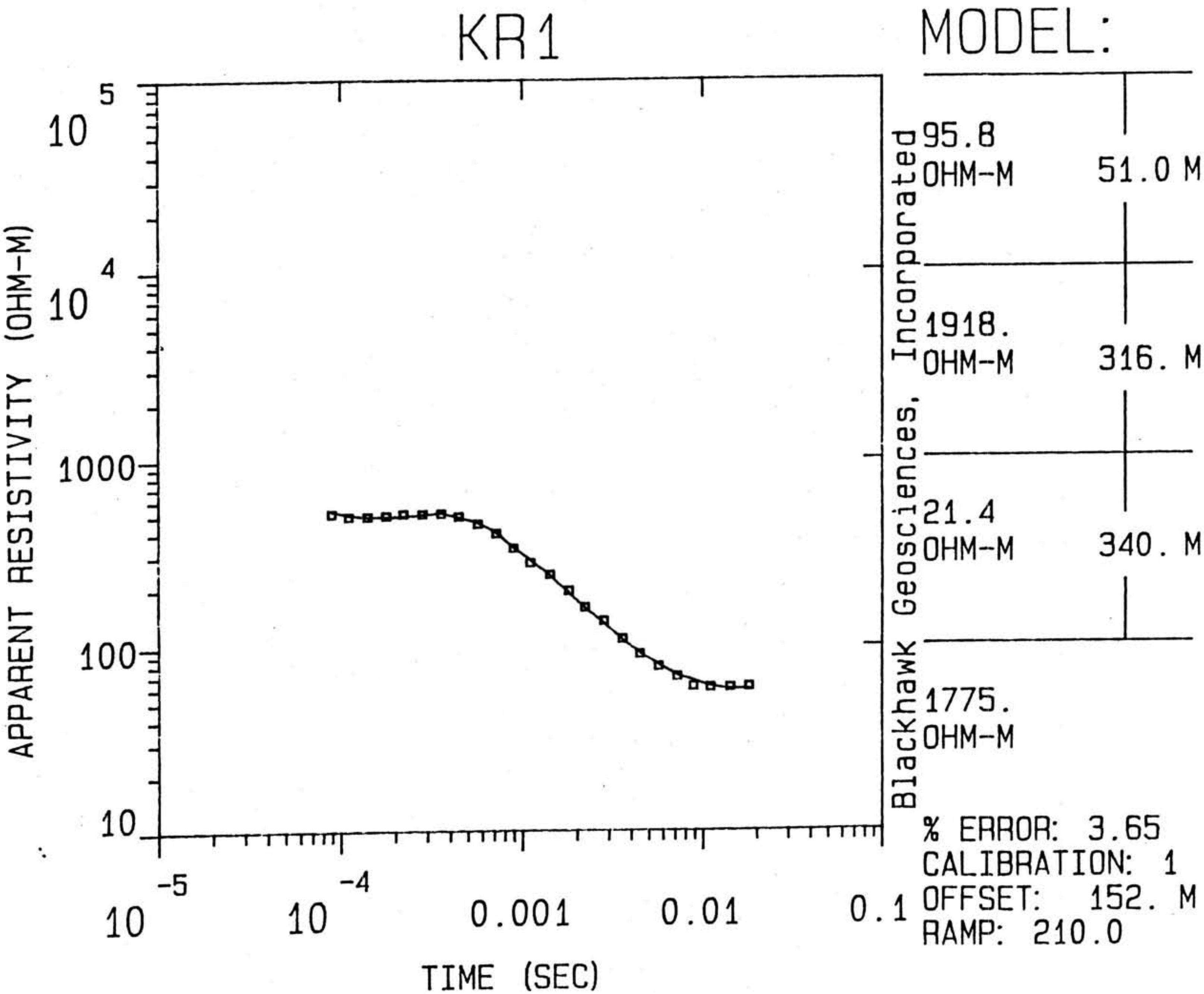

KR1
MODEL:
95.8
OHM-M
51.0 M
1918.
OHM-M
316. M
21.4
OHM-M
340. M
1775.
OHM-M
% ERROR: 3.65
CALIBRATION: 1
OFFSET: 152. M
RAMP: 210.0
Blackhawk Geosciences, Incorporated
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
TIME (SEC)
10^{-5}
10^{-4}
0.001
0.01
0.1

FIGURE 3-1

FIGURE 3-2

KR1

MODEL : 4 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		579.1	1900.0		
95.78	51.0	528.1	1732.6	0.5	0.5
1918.02	316.3	211.8	694.8	0.2	0.7
21.40	339.5	-127.7	-419.1	15.9	16.6
1774.88					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	5.09E+02	5.26E+02	-3.141	
2	1.10E-04	4.90E+02	4.99E+02	-1.693	
3	1.40E-04	4.91E+02	4.86E+02	1.058	
4	1.77E-04	4.96E+02	4.88E+02	1.606	
5	2.20E-04	5.06E+02	4.94E+02	2.547	
6	2.80E-04	5.05E+02	5.04E+02	0.196	
7	3.55E-04	5.07E+02	5.13E+02	-1.261	
8	4.43E-04	4.88E+02	4.80E+02	1.563	
9	5.64E-04	4.45E+02	4.52E+02	-1.521	
10	7.13E-04	3.95E+02	3.99E+02	-1.130	
11	8.90E-04	3.27E+02	3.29E+02	-0.409	
12	1.10E-03	2.73E+02	2.81E+02	-2.843	
13	1.41E-03	2.35E+02	2.32E+02	1.523	
14	1.80E-03	1.94E+02	1.87E+02	3.585	
15	2.20E-03	1.59E+02	1.56E+02	1.501	
16	2.80E-03	1.34E+02	1.30E+02	3.090	
17	3.55E-03	1.08E+02	1.07E+02	1.757	
18	4.43E-03	9.06E+01	9.13E+01	-0.692	
19	5.64E-03	7.79E+01	7.90E+01	-1.382	
20	7.13E-03	6.86E+01	6.96E+01	-1.438	
21	8.81E-03	6.07E+01	6.49E+01	-6.573	
22	1.10E-02	6.00E+01	6.06E+01	-0.967	
23	1.41E-02	5.99E+01	5.83E+01	2.780	
24	1.80E-02	6.03E+01	5.85E+01	3.120	

R: 152. X: 0. Y: 153. DL: 305. REQ: 170. CF: 1.0000
TDHZ ARRAY, 24 DATA POINTS, RAMP: 210.0 MICROSEC, DATA: KR1
0604 0001 0001 Z OPR XTL H 4 10+100
Ch.21 = 0.21 Ch.22 = 0.089 Ch.23 = 20 Ch.24 = 9
RMS LOG ERROR: 1.56E-02, ANTILOG YIELDS 3.6503 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER
P 1 0.94
P 2 -0.03 0.05
P 3 0.01 -0.02 0.97

4.0 INTERPRETATION RESULTS

4.1 GENERAL

The main objective of the geophysical survey is not to obtain the resistivity layering of the subsurface, but to infer from the resistivity layering information about the elevation and thickness of the fresh water resource. The translation of resistivity layering into meaningful hydrogeologic information is generally accomplished in two ways:

1. Using available knowledge about the relation between resistivity values and hydrogeology. For example, in the volcanic rocks of Hawaii, rocks saturated with salt water will generally have resistivities less than 5 ohm-m. On the other hand, dry and fresh water/brackish water saturated volcanic rocks and intrusives can have very high resistivities (greater than 1,000 ohm-m).

2. Calibrating the geophysical interpretation at a well. In this case several wells were available for comparison. The approximate location of these wells are shown in Figure 2-1. The two wells (#1 and 2) located at lower elevation (1,460 ft) had static water levels (heads) of 6 ft above sea level. The well #3 located at higher elevation (1,835 ft) had a head of approximately 150 ft above sea level. This large difference in heads over the approximate 4,000 ft distance can best be explained by major geologic structures (rifts, dikes, etc.) which act to dam ground water flow.

In the case where a very conductive layer is detected below sea level in the TDEM interpretation, then the layer is expected to be caused by saline saturated volcanics. Static water levels (heads) can be calculated from these soundings by using the Ghyben-Herzberg relation. This relation, however, assumes hydrostatic equilibrium and is not expected to apply to soundings in close proximity to ground water damming structures.

The soundings acquired in a large area around wells #1, 2 and 3 did not detect salt water saturated volcanics below sea level. The behavior of the ground water in these areas is, therefore, expected to be dike or structure controlled. Other TDEM soundings in the survey area were able to detect salt water saturated volcanics below sea level, and for these soundings ground water levels may behave according to the Ghyben-Herzberg relationship.

4.2 GEOELECTRIC CROSS-SECTION

The results of some the TDEM interpretations are presented as a south to north geoelectric cross section in Figure 4-1. In the geoelectric section layers with similar resistivities have been linked together. In the geoelectric section soundings 6W and 4W (on the south) and soundings 10 and 16 (to the north) show similar three-layer sequences. The upper surface layer (44 to 220 ohm-m) is interpreted to represent soils or weathered volcanics. The intermediate layer of very high resistivities (> 5000 ohm-m) is interpreted as unweathered volcanics. The portions of this layer below sea level are expected to contain fresh or brackish water. The deepest layer in the section with resistivities of 4.2 to 9.6 ohm-m is interpreted to represent salt water saturated volcanics.

In the geoelectric section beneath soundings 3W, 3, 8 and 13 a more complex layering sequence is interpreted. A third layer which exhibits resistivities from 2 to 22 ohm-m is interpreted as volcanic ash flows or altered volcanic occurring above and below sea level. The lowest layer beneath soundings 3, 8 and 13, with resistivities of 1030 to 1672 ohm-m, probably represents unaltered volcanics or intrusives to the maximum search depth (≈ 3,000 ft). Generally, it is difficult to discriminate between unaltered volcanics which are dry or which contain fresh or brackish water (less than 250 ppm chloride). The reason is that, in addition to salinity, changes in porosity and lithology also influence formation resistivity.

Within the geoelectric section several vertical structures are interpreted. These structures are likely caused by vertical dikes of impermeable rocks resulting in a barrier to ground water flow which may explain the high level ground water head (150 ft) at well #3.

4.3 INTERPRETATION MAP

In order to incorporate all the soundings into one data set, an interpretation map of the TDEM results for the Kohala Ranch area was constructed (Fig. 4-2). In this figure the soundings which detected saline saturated volcanics below sea level are separated from the soundings which have a resistive basement (or conductive basement which occurs above sea level). In other words, soundings which are expected to represent basal saline water are separated from soundings which are influenced by dike impoundment or other geologic structures.

In this figure the elevation of the top of the salt water interface derived from the TDEM measurements is contoured. These values will be approximately equal to the thickness of the fresh-brackish water lens if the basal water is in equilibrium. In addition to the TDEM data, static water level (heads) from three wells drilled on the ranch property are shown on the contour map (information furnished by Nance, 1990, personal communication).

The main features evident in the interpretation map are:

(1) Areas outside the boundary between impounded and basal water generally show the salt water interface to deepen towards the northeast. On the south side of the boundary the depth to basal saline water increases rapidly with increasing elevation. On the north side of the boundary the depth to saline water increases gradually with increasing elevation.

(2) The area interpreted to be effected by confining structures extends in a narrow zone from about 1,000 ft above sea level near sounding 4 and widens with increasing elevation towards the northeast. Wells #1 and #2 also lie within the interpreted dike confined water zone.

Within the boundary the TDEM data can be grouped according to comparable model results. Soundings 2, 4, 11 and 14 (near wells #1 and #2) have similar two-layer model results. These soundings show a thick resistive (280 to 497 ohm-m) layer above a conductive layer (3 to 5 ohm-m) both occurring above sea level. This lower conductive layer is most likely interpreted as volcanic ash flows or altered volcanics.

Soundings 1, 8 and 13 in the vicinity of well #3 have comparable model results. Each sounding shows a four-layer sequence (Fig. 4-1) with the deep resistive layer (1049 to 1775 ohm-m) interpreted as unaltered volcanics or intrusives. Sounding 7, which does not fit in either of these two grouped areas exhibits a three-layer sequence with a lower resistive (181 ohm-m) layer occurring approximately 748 ft below sea level. This lower layer may also be best interpreted as unaltered volcanics or intrusives.

Soundings 3 and 15 have similar four-layer model results with a resistive lower layer (1030 to 1688 ohm-m) occurring above sea level. This layer is most likely interpreted as unaltered volcanics or intrusives.

Models for soundings 2W and 3W are similar to each other, but are quite different from surrounding soundings (Fig. 4-1). These soundings are located close to the interpreted boundary between basal and dike-confined water. This closeness to the boundary may be the reason for differences seen between these sounding sets.

Soundings 5 and 12 have similar three layer model results. Both soundings show a resistive (79 to 360 ohm-m) layer at depth occurring below sea level. This lower layer can best be interpreted as unaltered volcanics or intrusives.

4.4 HYDROGEOLOGIC INTERPRETATION

The geophysical interpretation (Fig. 4-2) outlined two areas of different hydrogeologic parameters, i.e., an area in which the ground water is expected to be controlled by geologic structures (dikes, intrusives, etc.) and an area in which the ground water is expected to occur mainly in the basal mode. Within the area interpreted to be controlled by geologic structures, the hydrologic parameters such as static head and volume of the ground water resource, cannot be inferred from the geophysical data. This is due to the fact that the presence or absence of fresh water has little effect upon the electrical resistivity measured by the TDEM method. In areas with comparable TDEM results (see Section 4.3) it can be assumed that similar hydrologic parameters may exist. For example, soundings 1, 8 and 13 near well #3 all display similar results, and therefore likely outline the extent of the structure which creates the anomalous head at well #3. Similarly, the soundings around wells #1 and #2 (11, 2, 14, and 4) all display similar results and could be expected to define the boundary of the lower heads seen in these wells. Geologic structures are inferred between separate groups of soundings with similar results (reference Figs. 4-1 and 4-2).

In the area interpreted to be represented by basal water resources, the fresh water resource can be estimated by the volume between sea level and the elevation of the interpreted saline water. If this water can be assumed to be hydrostatic equilibrium, then the static water level (head) can be calculated using the Ghyben-Herzberg relation. Table 4-1 shows the thickness of the fresh/brackish water lens obtained directly from the model results for each sounding.

Table 4-1. <u>Hydrogeologic information derived from TDEM soundings</u>

Sounding #	Surface Elevation (ft)	Approximate Thickness of Fresh/Brackish Water Lens (ft)
6	1550	272
9	1420	204
10	1850	419
16	1890	295
1W	830	98
4W	1665	771
5W	1340	484
6W	1450	778
7W	1680	905
8W	1885	1000?

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the TDEM survey at KRD are summarized in Figure 4-2. In this figure areas of the development in which ground water is expected to be controlled by geologic structures (dikes, intrusives, etc.) are separated from the area in which the ground water is expected to exist in the basal mode. The ground water resources within the area controlled by geologic structures cannot be determined directly from the TDEM data, however, sub-zones in which the hydrologic parameters are expected to be the same have been identified. For example, soundings 1, 8 and 13 near well #3 all exhibit similar behavior, and therefore can be expected to define the limits of the structure in which well #3 was positioned. Structures are inferred to exist between groups of soundings with similar results.

In the area interpreted to be represented by basal water resources, the fresh water resource is expected to be the volume between sea level and the elevation of the interpreted salt water. If the area can be assumed to be in hydrostatic equilibrium then the static water level (head) can be calculated using the Ghyben-Herzberg relation. The applicability of the Ghyben-Herzberg relationship in the area is expected to be marginal due to the existence of ground water damming structures.